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Analysis of right-turn lane length in left-hand traffic countries at signalised intersections of urban roads

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Analysis of Right-Turn Lane Length in Left-Hand Traffic Countries at Signalised Intersections of Urban Roads

By

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This thesis is presented in fulfilment to the requirements for the
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Edith Cowan University

School of Engineering

USE OF THESIS

The Use of Thesis statement is not included in this version of the thesis.

ABSTRACT

Analysis of the right turn lane length of urban roads in left-hand traffic countries, such as Australia, UK and India (left-turn lane length in right-hand traffic countries such as USA), at signalised intersections encounters two main geometric features namely, deceleration length and storage length. The literature shows that in routine practice, the deceleration length is generally estimated by using constant deceleration rate. Many researchers consider this assumption for all design speeds unrealistic as it does not reflect the influence of the pavement condition. Hence, it may be desirable to consider the pavement's condition in terms of its longitudinal coefficient of friction in the design analysis. In regard to the storage length, a large number of the current guidelines and models estimate the storage length of right-turn lane at signalised intersections under split phase. Hence, there is a need to examine other phase types and timings and integrate the signal timing as a part of the geometric design

In this thesis, two analytical expressions have been analysed for the design of deceleration length. The first expression assumes a constant deceleration rate, and the second expression employs the concept of forces on a rotating wheel in which the coefficient of longitudinal friction between a vehicle's tyres and the road surface is considered. The calculated deceleration lengths by these two expressions were compared with the recommended values in American and Australian standards as well as with the deceleration lengths that were obtained by a recent simulation study presented in the literature. It has been found that applying a constant deceleration rate of 2.74 m/s^2 in the first expression provides the values of deceleration length comparable to most guidelines and studies. The second expression highlights the importance of using the pavement design in terms of the coefficient of friction to reduce the deceleration length in the case of limited space.

A MATLAB based simulation programme has been developed to provide an estimate of the right-turn lane storage length for different traffic volumes in order to avoid the problems associated with blocking and overflow of right turn vehicles in 95% of cycles. In established intersections that cannot be modified due to physical constraints, the model is flexible enough to examine different signal phase types and timings and provides other solutions to reduce overflow and/or blockage situations. The simulation model also takes into consideration the leftover queue. The model results have been compared against an available analytical method in which similar signal phases and timings were investigated. The outcomes are similar to those of the analytical model in most of the signal phase types. The

simulation model provides the flexibility to estimate the right-turn lane length for different combinations of through lane and right-turn lane traffic volumes.

The developed simulation model has also been validated against the field data using three parameters, namely 95th percentile of maximum queue, overflow cycle percentage, and blockage cycle percentage. Comparing with the field observations yields a level of accuracy in the range of 78%-85%. Finally this simulation model has been used to optimise the green time in the case of split phase that demonstrates a large difference in traffic volumes of two opposite approaches; this could reduce the mean wait time by up to 28%.

DEDICATION

To my late mum, your words, memories and prayers are the rock of my life on which I lean during challenging times.

To my four children Mina, Marina, Matthew and Mariah, I could not have done it without you.

ACKNOWLEDGEMENTS

I would like to gratefully acknowledge the help I received from several sources.

My sincere gratitude goes to my principal supervisor, Associate Professor Sanjay Kumar Shukla, for giving me this great opportunity to work on this research. His invaluable guidance, patience, encouragement, and support will always be appreciated.

My sincere gratitude goes to my co-supervisor Dr Steven Richardson for helping me solve many problems and providing me with many insightful suggestions. Without his involvement, this work would not have been possible. His encouragement and kindness will always be remembered.

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I would like from the bottom of my heart to thank my dear friend and sister Mrs Maha Ahmed Samir for her encouragement, care and support.

I would also like to acknowledge my beloved sons Mina Thomas and Matthew Thomas for their beneficial discussion and thoughtful support throughout my studies. A special thank goes to my adored daughters Marina Thomas and Mariah Thomas who kindly helped me in many ways to accomplish my research.

Above all I would like to give glory to God for the great strength and abundance grace given to me to accomplish this work.

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Signed

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NOTATIONS

a	deceleration rate (m/s^2)
C	cycle length (h)
c	cycle length (s)
c_g	lane group capacity (veh/h)
C_L	the lane group capacity per lane (veh/h)
G	green time in time unit
G_r	grade in algebraic percentage
G/C	ratio of green time to cycle length (cycle split) for the turning lane phase
g	gravity acceleration = 9.81 m/s^2
g_t	green time per cycle in second
HVT	heavy vehicle through percent
HVL	heavy vehicle left-turn percent
I	the upstream filtering factor for platoon arrivals.
K	a constant to reflect the random arrival of vehicles (ranged between 1.5: 2)
k_B	the incremental queue factor
L	storage length in unit length
LTV	left turn volume (veh/h)
M_{track}	vector indicating which cars in the through lane want to go straight (0) and which cars want to turn (1) but cannot get into the turning lane due to a blockage/overflow situation
n	number of vehicles in the queue

N_o	average overflow queue in vehicles
N_m	Maximum back of the queue in vehicle
N_{cr}	Critical queue –The maximum queue length in vehicle
N_C	number of cycle /hours.
OV	opposing volume (veh/h).
P_n	probability of n vehicles in the queue.
PF_2	queue progression factor
p	probability that an arriving vehicle wants to turn
Q_p	capacity in vehicle per unit time - maximum number of departure per hour
Q	the queue length in the back of queue model in vehicle (veh)
Q_1	the first term represent the uniform part of the back of queue model (veh)
Q_2	the second term represent the overflow part of the back of queue model (veh)
Q_u	the basic first term of queue for uniform non platooned arrival (veh)
Q_{bl}	average initial queue demand per lane (veh)
q	arrival flow rate-average number of arrival per hour (veh/h)
q_s	arrival flow rate –average number of arrival per s (veh/s)
R_p	platoon ratio = V_{Lg}/V_L
S	saturation flow in (veh/h)
s_t	saturation flow in (veh/s)
S	average queue storage length per vehicle unit length.
s_d	deceleration length in unit length

S_f	lane saturation flow in number of equivalent passenger car per hour of green time (pcphg)
S_{dept}	departure rate of through travelling vehicles (veh/s)
Sp	vehicle speed in mph
S_m	number of vehicles in the through lane in simulation model
S_L	the group saturation flow rate per lane (veh/h)
T_f	flow period in which an average q flow rate arrival appears (hour)
TV	through volume (veh/h)
T_m	number of vehicles in the turning lane in simulation model
T	number of vehicles in the turning lane
t_{max}	simulation duration (s)
t_{gap}	minimum time gap between opposing vehicles to allow permissive turning
T_{max}	maximum vehicle capacity of turning lane
T_{dept}	departure rate of turning vehicles (veh/s)
u	ending speed (m/s) = 0 in case of stopping
u_r	Green ratio
v_d	design speed(m/s)
v	average number of vehicles per unit time at a point upstream of back of queue (veh/s or veh/h)
v_1	right- turn volume in equivalent passenger car per second (pcps)
v_r	traffic volume of right turn lane in number of vehicle
v_s	traffic volume of the through lane in number of vehicle (veh/h)
V_L	lane group arrival flow rate per lane in veh/h

V	right-turn flow rate during the peak hour in vehicle per hour (veh/h)
V_{Lg}	is the arrival flow rate during green time in veh/h
x	the degree of saturation $= q/Q_p$
x_0	the degree of saturation when reached or below, the average overflow queue ≈ 0
X_L	is the lane group degree of saturation $= V_L / C_L$
X_u	the degree of saturation ratio at the upstream intersection v/c .
y_L	lane group flow ratio $= V_L / S_L$
z	$x - 1$
μ	service rate in (pcps).
μ_f	coefficient of friction.
λ_1	arrival rate, in equivalent passenger cars per second (pcps).
λ	average time between arriving vehicles (s)
λ_{oppose}	average time between arriving vehicles in the opposing through lane (s).

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CHAPTER 1

INTRODUCTION

1.1 General

Providing exclusive turn lanes at signalised intersections is important for maintaining traffic flow in the through lanes and ensuring safe manoeuvring of turning vehicles. Particularly at signalised intersections, segregated turn lanes increase the capacity of the intersections and reduce the cycle length and consequently minimise delays (Kikuchi et al., 2007).

Designing right-turn lanes (left-turn lane in right-hand traffic countries) is complex particularly due to the imposed constraints by opposing traffic at a typical signalised intersection (Figure 1.1). According to various American national and state guidelines such as American Association of State Highway and Transportation Officials and Texas department of Transportation (AASHTO, 2004, TxDOT, 2006) as well as Australian guidelines (Austroads, 2009), the right-turn lane length comprises two main parts: storage length and deceleration length, with the latter divided into two parts as: the taper length to allow for a gradual transition and manoeuvring into the right-turn lane (RTL) and to indicate the start of the turn lane; and the full width part for complete and safe deceleration (Figure 1.2).

Although AASHTO guidelines (2001, 2004) state that it is desirable for a turning vehicle to decelerate when it completely enters the RTL, AASHTO accepts that the deceleration could start in the through lane (THL) and considers taper length as part of the deceleration length.

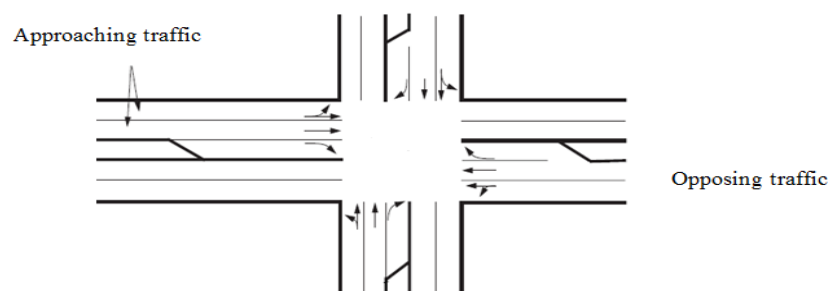


Figure 1.1 Geometric layout of a typical intersection.

While Australian guidelines (Austroads, 2009) provide explicit values for taper length as a function of the design speed for a lane width of 3.5 m (Table 2.1), TxDOT guidelines (2006) recommend a fixed taper length of 15.2 m (50 feet) for design speeds less than 72 km/h (45mi/h) and 30.5 m (100 feet) for higher speeds. However, AASHTO (2001, 2004) provides a taper length that is a ratio of taper length to lane width between 8:1 and 15:1 (longitudinal to transverse). Longer taper is recommended for high speed roads; however, it is advisable to use a shorter taper for clear indication of the RTL start and to maximise the full width part length.

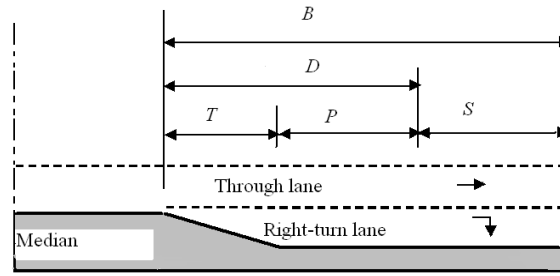
1.2 The Need for Deceleration and Storage Lengths

The deceleration length component is needed for a vehicle to safely and comfortably stop for a red light, or to give way to opposing traffic when required. The deceleration length is significant in RTL length design particularly in signalised intersections especially in off-peak hour when the length of the right turn lane should be sufficient for a vehicle travelling at the speed limit to stop without applying exorbitant deceleration that may cause rear end crashes and discomfort for drivers and/or passengers. (Qi et al., 2012).

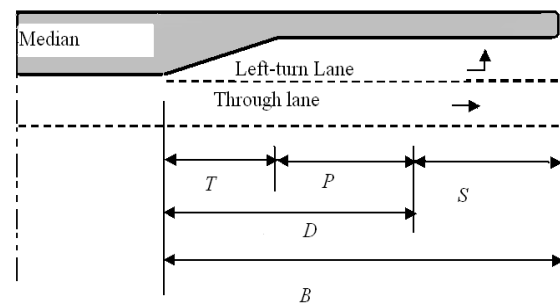
The storage length is required to store the waiting cars during a red signal or during a permissive phase in which the cars await for an appropriate time gap to make the turn and clear the intersection. This length should be designed to accommodate the longest anticipated queue and thus prevents overflow into the through lane causing its blockage or the accumulation of the cars in the THL that may block the access to the RTLs

The storage length in particular is complex due to several variables and the inherent randomness of the arrival and departure rates. Some of these variables are associated with the signal phase type and timing and others with traffic parameters such as THL and RTL traffic volumes, arrival rates and headway.

While overestimating the RTL length would result in an unnecessary increasing costs, it may lure drivers to take this lane unintentionally causing safety concern. (Qi et al, 2012). As noted above, underestimating RTL length can hinder the flow of the through traffic caused by turning cars overflow or the blockage of RTL by the THL queue. The overflow and the blockage situations are depicted in Figures 1.3a and 1.3b, respectively. Notably the current guidelines only consider the overflow situation and ignore the blockage situation, however, this problem was addressed by several studies done by Kikuchi et al (1993, 2004, 2007, and 2010).



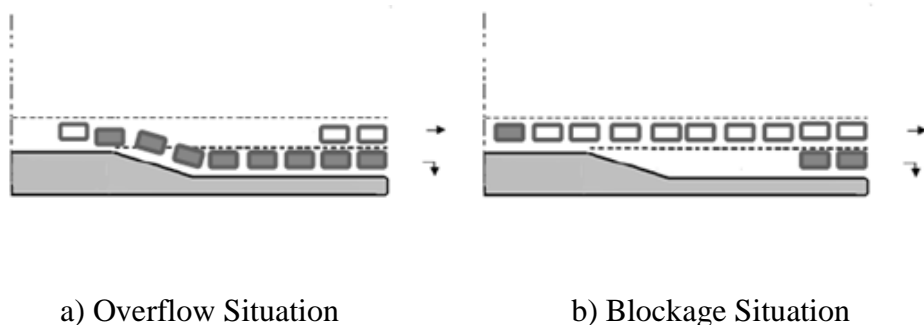
(a) Right-turn lane length in left-hand traffic countries



(b) Left-turn lane length in right-hand traffic countries

B = total length of right turn lane, D = deceleration length, S = storage length,
 T = Physical lane taper length, P = length of the parallel lane for deceleration

Figure 1.2 Illustration of the components of right-turn lane length and the corresponding left-turn lane in right-hand traffic countries such as the USA.



a) Overflow Situation

b) Blockage Situation

Figure 1.3 The blockage and the overflow situations (Adapted from Kikuchi et al, (1993))

1.3 The Design of the Right-Turn Lane Length

The RTL length should be sufficient for a car to manoeuvre into the RTL without reducing speed in the THL and disturbing the through traffic. The RTL length should be designed to

allow the car to decelerate while still providing enough storage length to accommodate the waiting cars as mentioned above.

The required deceleration length depends on the design speed and the comfortable deceleration rate, however, engineers find the task of determining a comfortable deceleration rate, challenging. They do not agree on one value.

In regard of the storage length, there are several methods to estimate the storage length of the RTL as summarised below:

1. The rule of thumb based method:

This method is used by most of the current guidelines (AASHTO, 2004), (TxDOT, 2006). However, it considers only the arrival rate, hence it overestimates the length in case of a high turning traffic volume and a high departure rate and underestimates the storage length in case of low arrival rate; see section 2.3.

2. Analytical based method:

This method relies on theoretical concepts such as queue theory and probability distribution. However it cannot model the stop and go characteristics of the queue at signalised intersections; see section 2.3.2

3. Simulation based method:

simulation based models would consider a reliable method in analysing traffic operations at signalised intersection considering all situations, but some of these models lack accuracy and /or require effort and time for calibration; see section 2.4.3.

1.4 Problem Statement

In relation to deceleration length design, there are two problems faced by engineers when they design the deceleration length required for a vehicle to stop: (1) which value do they consider as a comfortable deceleration rate to maintain an easy and safe stopping; (2) should they consider different values of deceleration rate proportional to vehicle speed. Due to the questionable assumption of constant deceleration rate, and the different evaluations of the comfortable deceleration rate, there is a need to evaluate the abovementioned guidelines and studies.

This study investigates and compares two analytical models of calculating the deceleration length for the RTL at signalised intersections. These models can also be used for calculating braking distance in other geometric feature designs. The first model relies on the assumption of a constant deceleration rate and the second model takes account of the friction

coefficient between the vehicle's tyres and pavement surface and its influence on deceleration rate. The latter model also considers the change of deceleration rate in relation to the vehicle's speed.

In relation to storage length estimation: the inherent randomness of the arrival of vehicles and the stop and go characteristics of the traffic at signalised intersections contribute to the complexity of the design of the RTL of traffic, thus traffic simulation is considered a useful approach for assessing traffic behaviour at signalised intersections (Qi et al., 2007). The Australian Standard (Austroads, 2009) also recommends the use of simulation software to simulate the intersection and analysing the data to estimate the required storage length based on the 95 percentile queue. However the existing simulation based software is either time consuming or lacking in accuracy, see (section 2.4). Moreover, although several methods have been developed to estimate the storage length, there have been few attempts to provide a flexible model for integrating signal phases and timings for the designing of the RTL length.

In this study a simplified simulation model for estimating the RTL storage length, has been developed for the right-hand traffic countries; however, the study is equally applicable to left-hand traffic countries.

Most of the current guidelines use the split phase system in which all the traffic movement of a certain approach has the right of way followed by all the movements of the opposing approach (Kikuchi and Kronprasert, 2010). In the case of fixed time cycle length, the phase timing is the same, regardless of the density of the opposing traffic volume. This study investigated a method for estimating an optimal green time for each approach based on the traffic volume.

1.5 Publication Based on the Present Work

Attempts have been made to write research papers; two papers have been prepared and they are currently almost in the final draft form as detailed below:

1. Thomas, N., Richardson, S. and Shukla, S. K. (2016). A Simplified Simulation Model to Estimate the Storage Length of the Right-Turn Lane in Left-Hand Traffic at Signalised Intersections for Different Signal Phases and Cycle Timings. *Transportation Research Record* (under preparation).

-
2. Thomas, N., Shukla, S. K. and Richardson, S (2016). Estimating deceleration lengths in right-turn pavement lanes at signalised intersections within left-hand traffic nations *International Journal of Pavement Engineering* (under preparation).

1.6 Organization of the Present Work

In this chapter, the research area is introduced and basic information for the research topic is described. A critical review of research on the design of RTL length in left-hand traffic countries, which corresponds to the left-turn lane in right-hand traffic countries, is presented in Chapter 2. Chapter 3 describes the design of the deceleration length. In Chapter 4, a simplified simulation model is developed to estimate the storage length. A validation of the simulation model using the field data is presented in Chapter 5. Chapters 6 investigates the optimal green time at the intersections with split phase signal type and different volumes of the approaching traffic in opposing directions as a case study. The summary of the thesis work with conclusions and further research challenges is presented in Chapter 7.

CHAPTER 2

LITERATURE REVIEW

2.1 General

Right-turn lane (RTL) length, particularly at signalised intersections, is a significant geometric aspect required to maintain the traffic flow and facilitate the right turn movement safely and effectively. According to several guidelines such as Austroads (2009) and TxDOT (2006), the RTL (left-turn lane in right-hand driving countries) length is comprised of taper length, deceleration length and storage length as illustrated in Figure 1.2 (see section 1.1). Those guidelines considered the taper length as part of the deceleration length. AASHTO (2001) assumed that the deceleration length is separate to the taper length and accordingly overestimated the deceleration length; however, this was rectified in AASHTO (2004) and the taper length considered to be part of the deceleration length.

The storage length design is more complex due to the random nature of the traffic flow and the signal types and timings. Thus many models were used by researchers to estimate the storage length. In general, there are three methods that have been explored by engineers to estimate the storage length: 1) the rule of thumb method, 2) The analytical based method, and 3) the simulation based method.

In the following sections, a brief discussion and background for each part of the right-turn lane lengths are concluded.

2.2 Taper Length

Austroads guideline (2009) identifies the taper length in term of the design speed and the lane's width. The taper length should not be too long so that drivers may accurately identify the beginning of the right-turn lane and avoid the unintentional entering to the lane, in addition, maximise the parallel lane for deceleration so it could be used towards the storage length.

AASHTO guidelines (2004) recommend the taper length as a proportional to the lane width (longitudinal: transverse) in a ratio between 8:1 for design speeds up to 30 mph (50

km/h) and 15:1 for design speeds up to 50 mph (80 km/h). Conversely, Austroads guideline (2009) provides a taper length relative to each design speed as in Table 2.1

Table 2.1 Length of physical taper for a 3.5 m lane width (Austroads, 2009)

Design Speed (km/h)	Taper Length (m)
50	15
60	20
70	23
80	25
90	30
100	33
110	35

2.3 Deceleration Length

The required deceleration length or braking distance for a vehicle to stop has been investigated as part of many road geometric features such as stopping sight distance, exit terminals and turn lanes. The design of deceleration length depends on deceleration rate and the operating speed of the vehicle, the latter is assumed to be the design speed in the present study, since recent data showed that drivers do not slow on the condition of wet pavement as was previously assumed (AASHTO, 2001). Bonneson, and McCoy (1997) established that drivers, when entering a turn lane applied a different deceleration rate depending on their entering speed. previous American and Australian guidelines attained to this variation by recommending different coefficients of longitudinal friction based on the design speeds, which is also referred to as longitudinal decelerations (AASHTO, 1994; Austroads 2002).

However, some researchers such as Fambro et al. (1997) and Durth and Bernhard (2000) highlighted the steady deceleration rate performance of the newer cars, that is relatively constant for different speeds. Taking this finding into consideration, updated American and Australian guidelines (AASHTO, 2001; Austroads, 2009) applied a uniform deceleration rate. Intriguingly, the latter guideline states that the deceleration rate depends on several parameters including vehicle speed, tyre condition and road surface; however, it specifies only one coefficient of deceleration (0.26) to evaluate the deceleration length for turn lanes at intersections regardless of the design speed of the roads. This coefficient

corresponds to a deceleration rate of 2.5 m/s^2 which was considered a comfortable deceleration rate (Austroads, 2009).

Apart from using a constant deceleration rate; the modern guidelines indicate different comfortable deceleration rate values which have been argued by many researchers and have been also investigated for evaluating braking distance required for stopping sight distance. Treiber et al. (2008) nominated a comfortable deceleration rate of 1.67 m/s^2 as a parameter for a proposed intelligent-driver model under a car-following situation, in which the driver is assumed to leave enough headway to enable safe stopping even when the preceding car applies its maximum brake force. Recently, Maurya and Bokare (2012) conducted an experiment to investigate the deceleration rate for different types of vehicles. The experiment's results showed that the maximum deceleration rates are 0.88 m/s^2 for trucks and 1.71 m/s^2 for cars, the latter is very close to the value suggested by Treiber et al. (2008). Notably these values were for vehicles under car-following conditions. Austroads (2009) guidelines stated two values of deceleration rate in the design of right-turn lane length, a comfortable deceleration rate of 2.5 m/s^2 and a maximum deceleration rate 3.5 m/s^2 , while Iowa State-Wide Urban Design and Specifications (2006) specified a value of 2.74 m/s^2 (9 ft/s^2) as a comfortable deceleration rate for design purposes. On the other hand AASHTO (2001) indicated deceleration rate of 1.5 m/s^2 as was observed in approaching uncontrolled intersections and increased gradually to 3.4 m/s^2 , which is the recommended deceleration rate when braking due to unexpected situation.

Overall those studies and guidelines do not convincingly address the impact of the design speed on deceleration rate and whether a constant deceleration rate is appropriate regardless of the design speed. Studies that relate deceleration rate to speed are reviewed below:

Ong and Fwa (2010) investigated braking distance in relation to pavement friction management, and established that the deceleration rate is influenced by the pavement conditions. Hence, they criticised guidelines that consider only one deceleration rate for all design speed regardless of the pavement condition and emphasised the importance of integrating pavement coefficients of friction to achieve an efficient geometric design. Bennett and Dunn (1995) observed deceleration rates values of 1.39, 1.79, 2.22 and 2.34 m/s^2 for speed of 60-70, 70-80, 80-90 and 90-100 km/h. respectively. These results implied that when speed increases deceleration rate tends to increase accordingly. Whereas Wang et al. (2005) presented deceleration rate values ranged between $2.67\text{-}2.55 \text{ m/s}^2$ for speed range of 60-90 km/h. The latter study indicates a similar trend to that of Akçelik and Basley (2001) who

reported a deceleration rate of 3.09 m/s^2 for speed of 60 km/h and $2.4\text{-}2.39 \text{ m/s}^2$ for speed range 40-60 km/h,. In general the observed deceleration rate by the majority of the studies is less or similar to the 3.4 m/s^2 value recommended by AASHTO (2001) as a comfortable deceleration rate when calculating the breaking distance.

Qi et. al (2012), using simulation software VISSIM, developed a relationship between the deceleration length and the deceleration rate in relation to various design speeds, the results showed that the 85th percentile of the deceleration rate range is $2.71\text{-}2.77 \text{ m/s}^2$ hence the deceleration lengths were considered based on the average deceleration lengths in this range, and were compared against TxDOT(2006), AASHTO(2001) and FDOT (2006) guidelines. However, in this investigation, the taper length recommended by TxDOT (2006) was used as an input for the simulation experiments as part of the total deceleration length, which may influence the findings. Qi et al. (2012) investigation concluded that the results obtained by the simulation based method and the deceleration length suggested by TxDOT. (2006) are similar, however, it was noted that at high speed, the deceleration length was noticeably less than the TxDOT recommendation.

According to AASHTO (2001, 2004) and Austroads (2009) the deceleration desirably should occur away from the through traffic lane to ensure the efficient operation of the intersections, in these guidelines the deceleration length comprises of the taper length and the length of the parallel part of deceleration, as shown in Figure 1.2. The deceleration length is determined based on two factors the design speed and the comfortable deceleration rate. Austroads guidelines provide two sets of estimates for the deceleration length, one correspond to a comfortable deceleration rate of 2.5 m/s^2 and the other was calculated using a maximum deceleration rate of 3.5 m/s^2 Table 2.2. The value for deceleration in Table 2.2 should be increased for the down grade and maybe reduced for an upgrade using the factors in Table 2.3.

Table 2.2 Deceleration distances required for vehicles on a level grade (Adopted from Austroads, 2009)

Design speed Km/h	Length of Deceleration D (m) Including Taper (T)	
	Comfortable deceleration rate 2.5 m/s ²	Comfortable deceleration rate 3.5 m/s ²
40	40	30
60	55	40
70	75	55
80	100	70
90	125	90
100	155	110
110	185	135

Table 2.3 Correction to deceleration distance according to grade (Austroads, 2009)

Grade	Ratio of length on grade to length on level (shown in Table 2.2)	
	Upgrade	Downgrade
0-2%	1.0	1.1
3-4%	0.9	1.2
5-6%	0.8	1.35

2.4 Storage Length

Several models have been developed to estimate the storage length of the RTL at signalised intersections based on different methods as discussed in the following subsections.

2.4.1 Rule of thumb method

Guidelines such as AASHTO (2004) and TxDOT (2006) prescribed a rule of thumb method by assuming that a storage length of 1.5-2 times the average number of turning vehicles during one cycle would be sufficient to cater for peak-hour traffic. The general formula of the rule of thumb method for signalized intersection is

$$L = K(V / N_c)S \quad (2.1)$$

where

L = storage length in unit length,

K = a constant to reflect the probability of storing the maximum expected queue (ranged between 1.5: 2),

V = right-turn flow rate during the peak hour in vehicle per hour (vph),

N_c = number of cycle /hour,

S = average queue storage length per vehicle per unit length.

This method does not consider the RTL departure rate but only the arrival rate; hence it may misjudge the appropriate RTL storage length. Moreover it only caters for the problem associated with the right-turn lane overflow and ignores the blockage situation.

2.4.2 Analytical method

There are many analytical models that were developed based on different theoretical consideration; some of these models will be discussed in the following sections.

2.4.2.1 Queuing theory-based method

Oppenlander and Oppenlander (1989) developed a model based on queue theory, assuming a Poisson random distribution for the arrival rate and an exponential distribution for the departure rate. The RTL queue was estimated using the following equation:

$$n = \frac{(\log P_n - \log(1 - \lambda_1 / \mu))}{\log(\lambda_1 / \mu)} \quad (2.2)$$

where

n = queue length in number of vehicles,

P_n = probability of n vehicles in the queue,

λ_1 = arrival rate (equivalent passenger cars per second (pcps)),

μ = service rate (pcps),

λ_1 and μ can be calculated as below:

$$\lambda_1 = 1.1v_1 / 3600,$$

$$\mu = S_f (G / C) / 3600.$$

where

1.1 = adjustment factor for the equivalence of right-turn vehicles with split phase,

v_1 = right turn volume, equivalent passenger car per hour (pcph),

S_f = lane saturation flow, number of equivalent passenger car per hour of green time (pcphg),

G / C = ratio of green time to cycle length for the RTL phase.

This model assumes a carry on serving queue ignoring the effect of signal phases on the traffic flow at signalised intersections. Similarly to the rule of thumb method, this model only considers the overflow of vehicles in the right-turn lane and does not consider the blockage situation.

2.4.2.2 Discrete time Markov chain based method (DTMC)

Kikuchi et al. (1993) used a discrete time Markov chain based method (DTMC) to estimate the queue length of the right-turn lane at signalised intersections. The DTMC reflects on preceding and present probabilities of states to predict the next state of the system, by considering a probability of right-turn lane overflow of < 0.02 and a probability of blockage due to through lane queue of < 0.1 ; emphasising the need to consider the blockage situation.

This method considers the problems associated with both overflow and blockage and also satisfies the continuous and the inherent randomness of the traffic flow as well as the impact of traffic signals on the right-turn lane queue; however, the model fell short of considering the leftover queue at the end of the green-phase that should be added to the formed queue during the red-phase in the proceeding cycle, thus this method results in underestimation of the queue length.

Qi et al. (2007) conducted field surveys at various signalised intersections and observed regular occurrences of the leftover queues in the left turn lane (RTL in the present study). Thus they developed a model for the leftover queue based on DTMC methods, underlining the need to consider the leftover queues in the design the left turn lane length to be adequate to store the longest predicted queue.

2.4.2.3 Vehicle arrivals in red phase based method

In order to account for the arrival flow during the red-phase and both the overflow and blockage problems, Kikuchi et al. (2004) developed a model for dual left-turn lanes (RTL in the present study) and a single through lane by considering a low probability (1% - 5%) of the occurrence of overflow or blockage problem based on the assumptions that the queues in the through lane and the right-turn lane are formed only during the red-phase. In common with Kikuchi et al. (1993) this neglects the carryover queues from the previous cycle. This assumption was examined and found to be unjustified as carryover queues were observed frequently (Qi et al., 2007) as mentioned before, however, it was a promising approach for dealing with the combination of overflow and blockage situations. The assumed length are shown in Table 2.4. It was concluded that when the average arrival rate of right-turn vehicles per red phase is small; the length of the turning lane is determined by the chance of blockage, and when it is large, the chance of the overflow situation is the critical factor.

Table 2.4 Computed length of left-turn lane for 16 cases of left-turn (right-turn) (LT) volume and through (TH) volume combinations ($\alpha = 0.95/0.99$) (After Kikuchi et al., 2004)

		LT per Red Phase (veh.)			
		8	14	19	25
TH per Red Phase (veh.)	8	13/15	13/16	14/17	17/19
	14	20/23	21/24	21/24	21/24
	19	25/29	26/30	26/30	27/30
	25	32/36	33/37	33/37	33/37

In an attempt to cater for all situations that may arise due to different signal phases and timings, Kikuchi and Kronprasert (2010) developed several formulas to calculate the storage length using a 5% threshold for blockage or overflow situations. This study

recommended storage lengths for different signal phases and timings, and traffic volumes in both through and turn lanes. The results indicate that the volume of the opposing traffic does not affect the the left turn lane (RTL in the present study) length when the right-turn lane volume is small. It also indicates that the leading RTL signal phase produces shorter lengths in comparison with the lagging right-turn phase.

In this study the storage length was calculated by assuming different green time for the RTL/THL based on the phase type and the turning probability values (Table 2.5)

Table 2.5 Green time for the right turn/through phase for different phase types extracted from Kikuchi and Kronprasert (2010)

Phase Type	Split Phase	PmO	PO			PPRT		
Turning probability			30%	50%	70%	30%	50%	70%
Green timing for 90 s cycle	22/22	45/45	17/28	21/24	25/20	15/30	19/26	25/20
Green timing for 120 s cycle	30/30	60/60	25/35	30/30	40/20	20/40	27/33	35/25

The storage length estimation were tabulated for various signal phase and traffic volumes for two cycle lengths 90 s and 120 s. as shown in Table 2.6

Table 2.6 Recommended left turn lane lengths (right-hand traffic countries) in number of vehicles (After Kikuchi and Kronprasert, 2010)

Approach Volume (vphpl)	Signal Scheme in Left-Turn in Right-Hand Traffic (Right-Turn in Left-Hand Traffic)							
	No Exclusive Left-Turn (Split Phase)	PmO Phase		PO Phase		PPLT Phase		
		Opposing Traffic (vphpl)				Opposing Traffic (vphpl)		
		200	600	Leading Left Turn	Lagging Left Turn	200	600	
Cycle Length =90 s, Percentage of Left-Turn Volume =30%								
200	4 (2-3)	3 (2)	3 (2)	4 (2-3)	4 (2-3)	4 (2)	4 (2)	
400	8 (4-5)	5 (2-3)	5 (2-3)	8 (4-5)	8 (4-5)	8 (2-3)	6 (2-3)	
600	11 (6-8)	8 (3-5)	8 (3-5)	11 (6-8)	11 (6-8)	11 (4-5)	9 (4-5)	
800	14 (7-10)	10 (5-6)	10 (5-6)	14 (8-10)	14 (8-10)	14 (5-6)	11 (5-6)	
Cycle Length =90 s, Percentage of Left-Turn Volume =50%								
200	4 (3-4)	3 (2-3)	3 (2-3)	5 (3-4)	5 (3-4)	4 (2-3)	4 (2-3)	
400	7 (6-8)	5 (4-5)	5 (4-5)	8 (6-8)	8 (6-8)	6 (4-5)	6 (4-5)	
600	10 (9-12)	7 (6-8)	7 (6-8)	11 (9-12)	11 (9-12)	8 (6-8)	8 (6-8)	
800	12 (12-16)	9 (8-10)	9 (8-10)	14 (12-16)	14 (12-16)	11 (8-10)	11 (8-10)	
Cycle Length =90 s, Percentage of Left-Turn Volume =70%								
200	4 (4-6)	3 (3-4)	3(3-4)	5 (4-6)	5 (4-6)	4 (3-4)	4 (3-4)	
400	8 (8-11)	5 (6-7)	5(6-7)	10 (8-11)	10 (8-11)	7 (6-8)	7 (6-8)	
600	11 (12-16)	8 (8-11)	8(8-11)	14 (12-16)	14 (12-16)	10 (8-11)	10 (8-11)	
800	14 (16-22)	10 (11-14)	10(11-14)	18 (15-20)	19 (15-20)	14 (11-14)	14 (11-14)	
Cycle Length = 120 s, Percentage of Left-Turn Volume =30%								
200	5 (2-3)	4 (2-3)	4 (2-3)	6 (2-3)	6 (2-3)	5 (2)	5 (2-3)	
400	10 (5-6)	7 (3-4)	7 (3-4)	10 (5-7)	10 (5-7)	9 (3-4)	9 (3-4)	
600	14 (7-9)	10 (5-6)	10 (5-6)	14 (8-10)	15 (8-10)	13 (5-6)	14 (5-6)	
800	19 (9-12)	13 (6-8)	14 (6-8)	18 (10-13)	20 (10-13)	16 (6-8)	18 (6-8)	
Cycle Length = 120 s, Percentage of Left-Turn Volume =50%								
200	5 (4-5)	4 (3-4)	4 (3-4)	6 (4-5)	6 (4-5)	4 (3-4)	4 (3-4)	
400	9 (8-10)	6 (5-7)	6 (5-7)	10 (8-10)	10 (8-10)	8 (5-8)	8 (5-8)	
600	12 (12-15)	9 (8-10)	9 (8-10)	14(11-15)	15 (11-15)	11 (8-11)	11 (8-11)	
800	16 (15-20)	11 (10-14)	12 (10-14)	19(15-20)	20 (15-20)	14 (10-14)	15 (10-14)	
Cycle Length = 120 s, Percentage of Left-Turn Volume =70%								
200	5 (6-7)	4 (4-5)	4 (4-5)	8 (5-7)	8 (5-7)	4 (4-5)	4 (4-5)	
400	10 (11-14)	7 (7-10)	7 (7-10)	12 (10-13)	13 (10-13)	7 (7-10)	7 (7-10)	
600	14 (16-21)	10 (11-14)	10 (11-14)	17 (15-20)	18 (15-20)	10 (11-14)	10 (11-14)	
800	19 (21-28)	13 (14-19)	14 (14-19)	22 (20-27)	24 (20-27)	13 (14-19)	14 (14-19)	

*The values in brackets are based on AASHTO (2004) recommendations.

2.4.2.4 The back of queue model

The back of queue model is adapted by the US Highway Capacity Manual (TRB 2000) and considered a significant improvement by introducing a time dependent expression which depends on the duration of analysis period. A brief discussion of the development of this model is discussed below.

Akçelik (1980b, 1998) developed a time dependent model using a coordinate transformation technique for translating the steady state function developed in an earlier study (Akçelik, 1980a) to a transition function that has the linear deterministic function as its asymptote (Figure 2.1). This method overcomes the problem associated with the steady state when the queue length tends to equal infinity as the volume ratio increases due to the unrealistic assumption that the system is in an uninterrupted steady state. In reality, any peak period ends at a point in time, and the arrival flow rate decreases long before a steady state is reached.

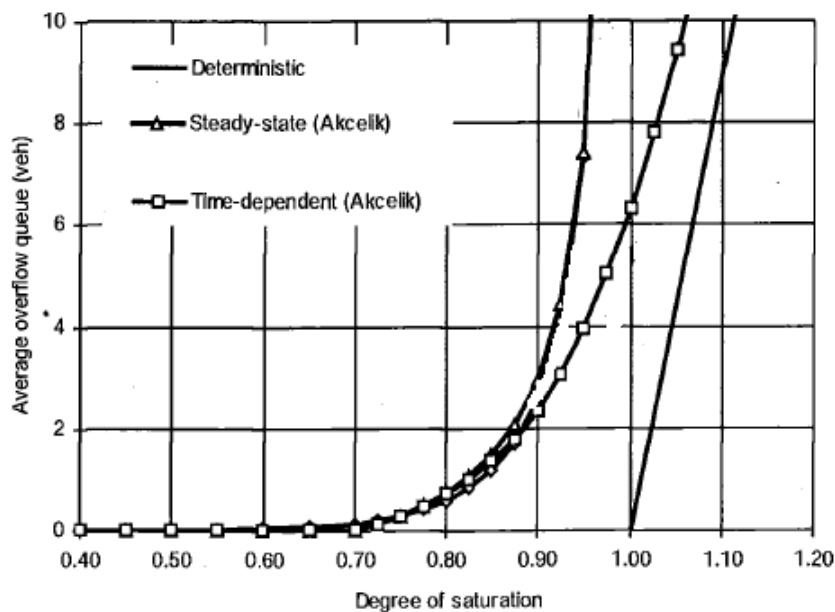


Figure. 2.1 The limitation of the steady-state and the deterministic models and using the coordinate transformation technique to achieve the time dependent model (Akçelik, 2001a).

In the time dependent model the expression of the queue length is comprised of two terms; the uniform part which is based on the assumption of regular arrival and related to red time and the overflow part which is based on the number of vehicles at the end of the green phase. This term is the time dependent expression of the model. It is important to note that

the concept of overflow in this literature is different to that of the previously mentioned, Kikuchi et al. studies.

The calculation of the overflow part of the queue length is determined by the situation of traffic whether it is under or over saturated. Akçelik (1980b) developed a formula to calculate the overflow queue N_o for over-saturated and under-saturated condition as shown below:

$$N_o = 0.25Q_pT_f \left(z + \sqrt{z^2 + \frac{12(x - x_o)}{QT_f}} \right) \text{ for } x > x_o$$

$$= 0 \text{ for } x \leq x_o \quad (2.3)$$

where

N_o = average overflow queue in vehicles

Q_p = capacity in vehicle/hour = $s(g_t / c)$

where

s is the saturation flow in vehicle/hour

and g_t / c is the proportion of effective green time to cycle time

T_f = flow period in which an average q flow rate arrival appear (hours)

$Q_p T_f$ = the maximum number of vehicles that can be dissipated during flow period

T_f

$z = x - 1$

x = the degree of saturation = q / Q_p

where

q = average arrival flow rate- number of arrival per hour veh/hour

x_o = the degree of saturation when achieved or below, the average overflow queue \approx

0 and is calculated by the following equation

$$x_o = 0.67 + s_t g_t / 600$$

where

s_t = the saturation flow in vehicle per second (veh/s)

g_t = the green time per cycle in second (s)

$s_t g_t$ can be identify as the capacity in vehicle /cycle

This formula provides a negative Z parameter in case of flow below capacity $x < x_o$ as was noted by Akçelik (2001a). The queue length adding the uniform part of the queue was given by the formula

$$N = q_s r + N_o \quad (2.4)$$

where

N and N_o are in number of vehicle (veh),

q_s = arrival flow rate in vehicle per second (veh/s),

$r = c - g_t$ (effective red time in second).(s)

Because the maximum back of queue is a function of the flow ratio, the equation was adjusted as follow

$$N_m = \frac{q_s r}{(1 - q_s / s)} + N_o \quad (2.5)$$

where

N_m = the maximum back of queue,

$q_s r$ and N_o are the same as in equation (2.4).

This equation was based on the theoretical presentation of the queue as a stacked number of vehicles at the stop line, technically the vehicles join the back of the queue in an incremental fashion thus this formula underestimates the queue length. Hence the maximum queue increases when the flow ratio increases, (mathematically this implies that in a congested situation, when the flow ratio > 1 , this equation is not applicable).

Furthermore, while the back of queue is building up, the vehicle in the front tends to move, by the time it reaches the maximum N_m , all vehicles would be moving some beyond the stop line, this implies that the maximum back of queue can differ in subsequent cycle.

It was also suggested that the calculation of the queue length should be based on critical value rather than maximum value as the equations presented above is a function of the average queue length.

$$N_{cr} = 2N_o \quad (2.6)$$

Akçelik (1980b) model was built on the assumption that the departure and the arrival rate are constant. Consequently, it is not applicable for permitted turn phase or more than one green phase in a cycle where the movement of traffic influenced by the opposed traffic behaviour, besides it did not cater for the platoon type of arrivals created by coordinate signals. Therefore, Akçelik (2001a) developed another model for HCM (2000) using a progression factor and adjusting the first part of the equation to cater for both the platoon type of traffic that is caused by coordinated signals and the random behaviour caused by permitted turns. Akçelik introduced the progression factor PF_2 in the first term of the equation as follow

$$Q = Q_1 + Q_2 \quad (2.7)$$

$$Q_1 = PF_2 Q_u = PF_2 \frac{V_L C (1 - u_r)}{1 - [\min(1, X_L) u_r]} \quad (2.8)$$

where

PF_2 = queue progression factor,

Q is the queue length in the back of queue model in vehicle (veh),

Q_1 is the first term represent the uniform part of the back of queue model (veh),

Q_2 is the second term represent the overflow part of the back of queue model (veh),

Q_u is the basic first term of queue for uniform non platooned arrival,

V_L = lane group arrival flow rate per lane in veh/h,

c_p = average cycle time in s,

$u_r = \frac{g_t}{c_p}$ Green ratio,

X_L is the lane group degree of saturation per lane = V_L / C_L ,

where

C_L is the lane group capacity per lane (veh/h).

PF_2 can be obtained using the following formula.

$$PF_2 = \frac{(1 - R_p u_r)(1 - y_L)}{(1 - u_r)(1 - R_p y_L)} \quad (2.9)$$

where

R_p = platoon ratio = V_{Lg}/V_L ,

where

V_{Lg} is the arrival flow rate during green time in veh/h,

y_L = lane group flow ratio = V_L / S_L

where

S_L is the group saturation flow rate per lane (veh/h).

In the second part which always represent the overflow part the equation as follow:

$$Q_2 = 0.25c_L T_f \left(z + \sqrt{z^2 + \frac{8k_B x}{c_L T_f} + \frac{16k_B Q_{bl}}{(c_L T_f)^2}} \right) \quad (2.10)$$

where

k_B is the incremental queue factor.

$k_B = 0.12(S_{Lg})^{0.7} I$ for pretimed signals,

$k_B = 0.10(S_{Lg})^{0.6} I$ for actuated signal,

and I is the upstream filtering factor for platoon arrivals,

$I = 1.0 - 0.91[\min(1.0, X_u)]^{2.68}$ for platooned arrivals,

$= 1.0$ for random arrivals

X_u = the degree of saturation ratio at the upstream intersection v/c_g .

Where

v_u = average number of vehicles per unit time at a point upstream of back of queue (veh/s or veh/h),

c_g = lane group capacity (veh/h),

Q_{bl} = average initial queue demand per lane,

$Q_{bl} = 0$ (no initial demand) and substitute in (2.10) will produce the following equation:

$$Q_2 = 0.25c_L T \left(z + \sqrt{z^2 + \frac{8k_B x}{c_L T}} \right) \quad (2.11)$$

Akçelik (2001b) provided six types of arrivals, that are shown in Table 2.6, based on lane usage and signal phasing .

While the introduction of the progression factor is considered a step to accommodate for platoon arrivals and permitted turn phase, it is built on many assumptions and constraints. The progression factor assumes that the queue dissipated time is the same for all progression types as a result of simplifying the formula. Thus this model still has limitations in regard to complex phases signals such as, protected permitted right-turn lane, two green signals per cycle or the platoon type of arrivals which could be created by coordinated signals.

Table 2.7 Arrival types, platoon ratios (R_p), and the proportion arriving during green (P) for various green times ratios. (Source: AkÇelik, 2001b)

Arrival Type	Progression Quality	Platoon Ratio (R_p)		Proportion Arriving During Green ($P=R_p u_r$)				f_{pA}
		Range	Default	$u=0.20$	$u=0.4$	$u=0.6$	$u=0.8$	
1	Very poor	≤ 0.50	0.333	0.067	0.133	0.200	0.266	1.00
2	Unfavourable	$>0.050-0.85$	0.667	0.133	0.267	0.400	0.534	0.93
3	Random arrivals	$>0.85-1.15$	1.000	0.200	0.400	0.600	0.800	1.00
4	Favourable	$>1.15-1.50$	1.333	0.267	0.533	0.800	1.000	1.15
5	Highway favourable	$>1.05-2.00$	1.667	0.333	0.667	1.000	1.000	1.00
6	Exceptional	>2.00	2.000	0.400	0.800	1.000	1.000	1.00

If the proportion of traffic arriving during green period (p) and the green ratio (u) are known, the platoon ratio R_p is calculated using the equation $R_p = P / u_r$.

*Note: f_{pA} is an additional adjustment value to calculate the delay progression factor it is not used to calculate the queue progression factor.

The easy flow of the through lane traffic can be influenced by the overflow situation; meanwhile the blockage can cause delay and frustration for right-turn lane users, Thus the solution has to determine the threshold probabilities of the blockage and/or the overflow occurrence. The problem is that the threshold probability is influenced by the level of service

and the type of intersections. In addition to the influence of the analysis period on the queue length, represented in the trajectory Figures 2.2a and 2.2b which illustrate the undersaturated back of queue and the oversaturated back of queue respectively, showing the significance of the leftover queue on the estimation of the maximum queue length.

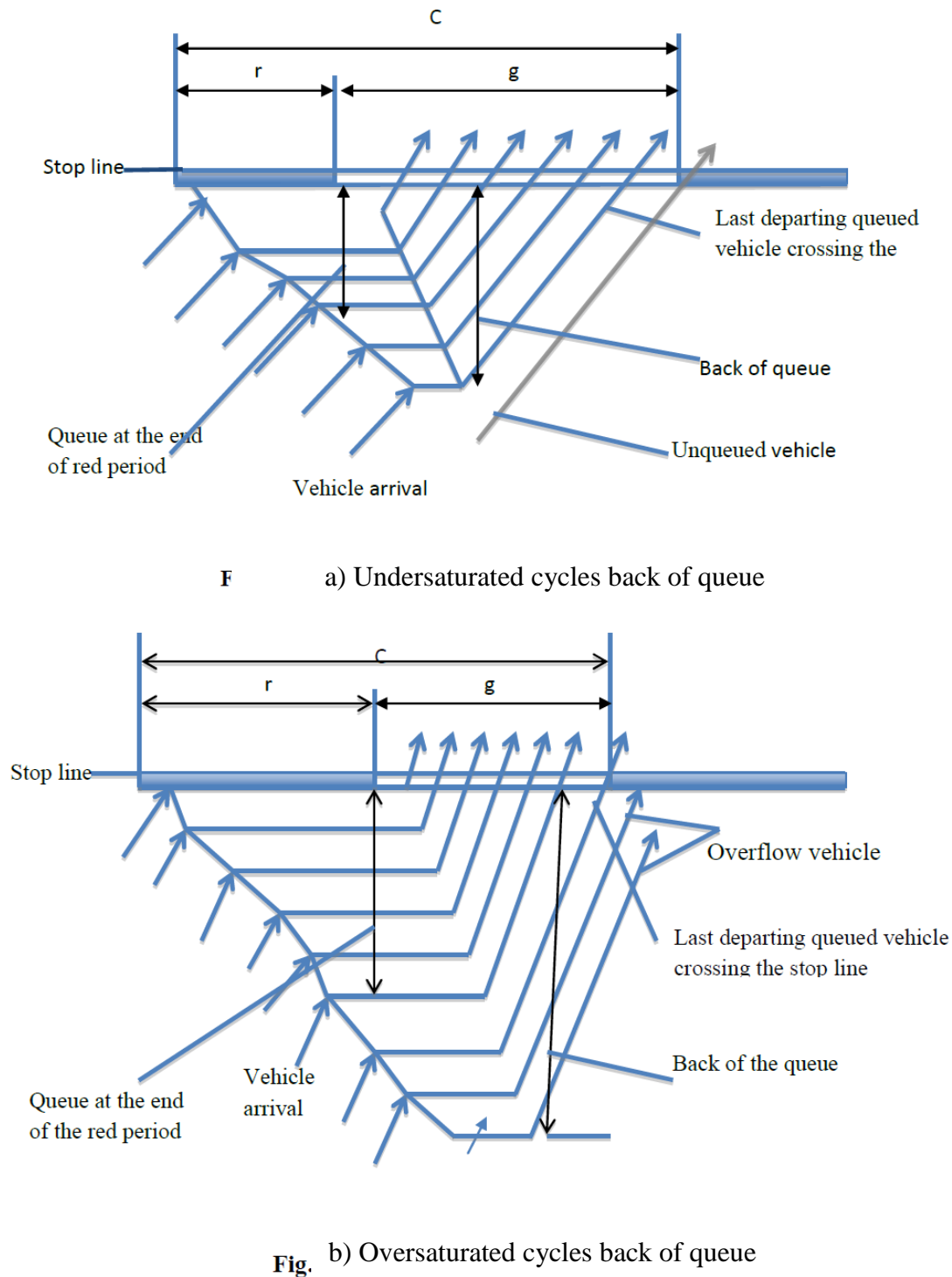


Figure 2.2 Trajectory of the back of queue model for both undersaturated and oversaturated cycles, r = red phase, g = green phase and C = cycle length (after HCM (2000)).

2.4.2.5 Incremental queue accumulation model

Strong and Rouphail (2005) contributed their research of the incremental queue accumulation (IQA) method to overcome the limitations of the previous model due to the assumption of uniform queue arrivals at the same point of the cycle

The IQA method is built on the idea of dividing the time to small equal-time intervals, and calculates the queue at the end of each interval by adding and subtracting the arrival and departure vehicles respectively at each interval then add this number to the queue at the beginning of that interval. This method was incorporated in complex turn phases include shared lane and was tested and validated by Mulandi and Peter (2011).

2.4.3 Simulation based model

Traffic simulation is a practical solution to estimate the storage length due to the random nature of the variables involved in the calculations. The following sections present a critical discussion and background of common simulation models.

2.4.3.1 Monte Carlo based simulation method

Oppenlander and Oppenlander (1996, 1999) conducted investigations using the Monte Carlo based simulation model, in which a random numbers can be used to simulate an event involving a number of variables. To estimate the probability distribution of the storage length. An assumption was made that the vehicles' arrival at the intersection follow Poisson distribution and the vehicles' departure follow triangle distribution. This study was only for signalised intersections that use a separate signal phase in which the right-turn movement is PO. Therefore, a more complex model was developed by Oppenlander and Oppenlander (2002) to calculate the storage length in permitted right-turn lanes. In addition to cycle length and green time the variable of opposing traffic volume was defined as any conflicting movement with the vehicle in the right-turn lane and was taken into consideration in the model. However, the simulation model did not consider the permissive protected phase that may be required during peak hours. A series of tables were developed for 50th, 85th and 95th percentile right-turn queue length in vehicle units for different values of the parameters involved (turning volume, cycle length, right-turn green time and opposing volume. Examples of these tables are shown in Table 2.8 for permitted signal phase. and Table 2.9 for separated signal phase.

Table 2.8 50th, 85th, 95th Percentile storage length in vehicle units for cycle duration 60 s, and effective green time 30 s. for permitted turn lane (without separate signal phase). (After Oppenlander and Oppenlander, 2002)

Left-Turn Lane 50 th , 85 th , and 95 th Percentile Storage Lengths (Vehicle Units)											
Without Separate Phase		Cycle Length = 60 s; Green Time=30 s									
Opposing Volume (vph)	Percentile Value	Left-Turn Volume (veh/h)									
		50	100	150	200	250	300	350	400	450	500
100	50 th	0	1	1	2	2	3	3	4	5	8
	85 th	1	2	2	3	4	5	5	7	10	18
	95 th	2	3	3	4	5	6	7	9	17	25
200	50 th	0	1	1	2	2	3	5	12	∞	∞
	85 th	1	2	2	3	4	6	10	23	∞	∞
	95 th	2	3	4	4	6	9	14	30	∞	∞
300	50 th	0	1	1	2	3	7	∞	∞		
	85 th	1	2	3	4	7	19	∞	∞		
	95 th	2	3	4	6	11	26	∞	∞		
400	50 th	0	1	2	4	38	∞				
	85 th	1	2	4	12	∞	∞				
	95 th	2	4	7	17	∞	∞				
500	50 th	1	2	15	∞	∞					
	85 th	2	5	29	∞	∞					
	95 th	3	11	35	∞	∞					
600	50 th	1	∞	∞							
	85 th	4	∞	∞							
	95 th	6	∞	∞							
700	50 th	∞									
	85 th	∞									
	95 th	∞									
800	50 th										
	85 th										
	95 th										

*Note: cells without entries represent infinite storage requirements

Table 2.9 50th, 85th, 95th Percentile storage length in vehicle units, cycle duration 60 s, for different effective green times, for separate signal phase (After Oppenlander and Oppenlander, 1996)

Lane Vol. (veh/h)	Percentile Value	Effective Green Time (s)						
		10	15	20	25	30	35	40
50	50 th	1	0	0	0	0	0	0
	85 th	2	1	1	1	1	1	1
	95 th	2	2	2	2	2	2	1
100	50 th	1	1	1	1	1	1	0
	85 th	3	2	2	2	2	2	1
	95 th	4	3	3	3	3	2	2
150	50 th	2	2	2	1	1	1	1
	85 th	4	3	3	3	2	2	2
	95 th	6	4	4	4	3	3	2
200	50 th	4	2	2	2	2	1	1
	85 th	9	4	4	4	3	3	2
	95 th	13	5	5	4	4	3	3
250	50 th	∞	3	3	2	2	2	1
	85 th	∞	6	5	4	4	3	3
	95 th	∞	8	6	5	5	4	4
300	50 th		5	3	3	2	2	2
	85 th		10	6	5	4	4	3
	95 th		14	7	6	5	5	4
350	50 th		32	4	3	3	2	2
	85 th		∞	7	5	5	4	3
	95 th		∞	9	7	6	5	5
400	50 th		∞	5	4	3	3	2
	85 th		∞	9	6	5	5	4
	95 th			12	8	7	6	5
450	50 th			11	5	4	3	2
	85 th			21	7	6	5	4
	95 th			27	10	8	6	5
500	50 th			∞	6	4	3	2
	85 th			∞	10	7	6	4
	95 th			∞	13	9	7	5
550	50 th				9	5	4	3
	85 th				16	8	6	5
	95 th				23	10	8	6
600	50 th				∞	6	4	3
	85 th				∞	10	7	6
	95 th				∞	13	9	7
650	50 th					8	5	4
	85 th					15	8	6
	95 th					19	10	7
700	50 th					19	6	4
	85 th					43	9	6
	95 th					55	12	8
750	50 th					∞	7	4
	85 th					∞	13	7
	95 th					∞	19	10
800	50 th						12	5
	85 th						25	9
	95 th						33	12

2.4.3.2 Traffic analysis software based method

Yekhshatyan and Schnell (2008) used traffic analysis software Synchro and SimTraffic to simulate the storage length under different conditions and applied multivariate regression analysis to identify the storage length as a function of all the parameters involved in the design (Table 2.10) for each case of signalised intersections operation such as protected right-turn, permitted right-turn in term of through volume, opposing volume, right-turn volume, heavy vehicle through percent, heavy vehicle right-turn percent, grade, and speed; and developed a series of equation that could be considered as empirical formulas.

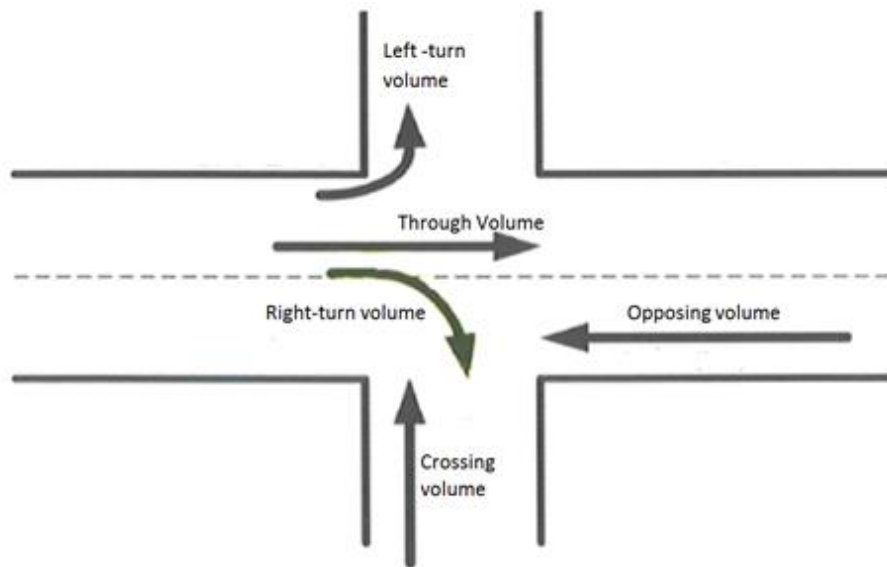


Figure 2.3 The variables involved in the design of the right-turn lane storage length in left-hand traffic countries (Adopted from Yekhshatyan & Schnell, 2008)

Table 2.10 The three components of the left-turn (right-turn in the proposed study) lane length, (Source: Yekhshatyan and Schnell, 2008)

Speed (mph)	Left Turn Lane Length		
	Deceleration	Taper	Storage Length (LT)
30	170	100	For protected left turns on signalised intersections $LT_{prot} = 35.3 + 0.0203 \times TV + 1.14 \times LTV - 0.171 \times Sp - 6.75 \times HVT + 1.32 \times HVL - 0.16 \times Gr$
35	170	100	
40	275	130	
45	340	130	
50	410	130	For permitted left turns on signalised intersections $LT_{perm} = -45.2 - 0.00953 \times TV + 0.0406 \times OV + 0.610 \times LTV + 0.348 \times Sp + 0.812 \times HVT + 1.76 \times HVL + 0.35 \times Gr$
55	485	130	
60	485	130	
65	485	130	
70	485	130	

where

TV = through volume in veh/h,

LTV = Left Turn Volume in veh/h,

OV = Opposing volume in veh/h,

HVT = Heavy vehicle through percentage,

HVL = Heavy vehicle left-turn percentage,

Sp = Speed in mph,

Gr = Grade in algebraic percentage.

The variables with regards to traffic volume are shown in Figure 2.3.

*Note that left- turn refers to right-turn and verse versa in the proposed study.

2.5 Current Traffic Software

The commercial software, HCS+, Synchro, SimTraffic and VISSIM are often used to calculate and/or simulate traffic at signalised intersections. Software such as HCS+ and Synchro are based on analytical method while SimTraffic and VISSIM are based on simulation method.

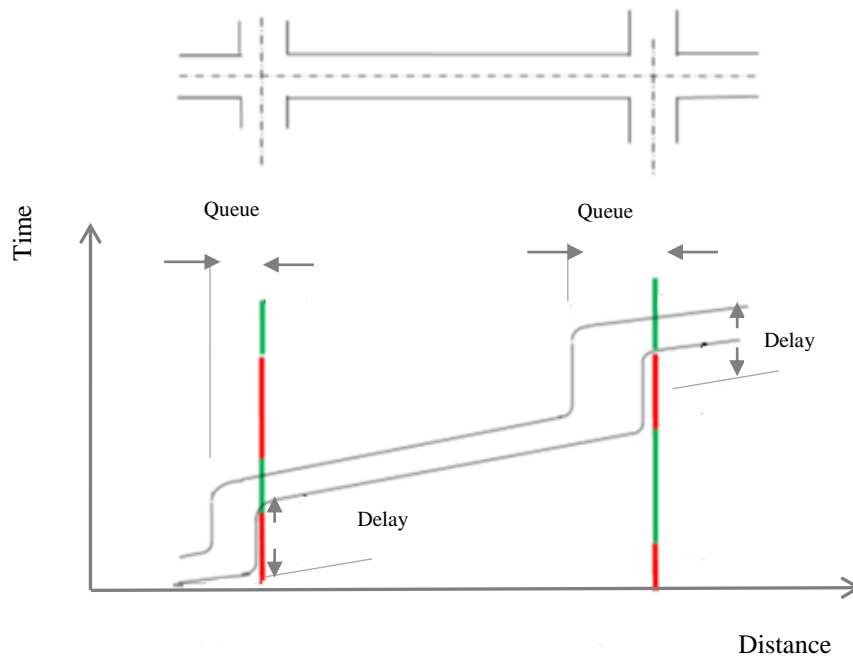
The performance of the aforementioned software was examined and compared against field data (Qi et al., 2012), and concluded that: 1. VISSIM overestimated the queue lengths in some cases due to a problem in separating the turn lane queue from the through lane queue when overflow and blocking situations occur; 2. SimTraffic results provided greater accuracy, however, it takes long time to calibrate and run the simulation.

The inherent randomness of the arrival of vehicles and the stop and go characteristic of the traffic at signalised intersections contribute to the complexity of the design of the right turn lane storage length. Thus traffic simulation is considered to be useful approach for inspecting the traffic behavior at signalized intersections (Qi et al., 2007). Australian Standards (Austroads, 2009) also recommend the use of simulation software, to simulate the intersection and analyse the data when estimating the required storage length based on the 95 percentile queue. However the existing simulation based software is either time consuming or lacks accuracy (Qi et al., 2012) Moreover, although several methods have been developed to estimate the storage length, there have been few attempts to provide a flexible model for integrating signal phases and timings into the design of the turn lane length.

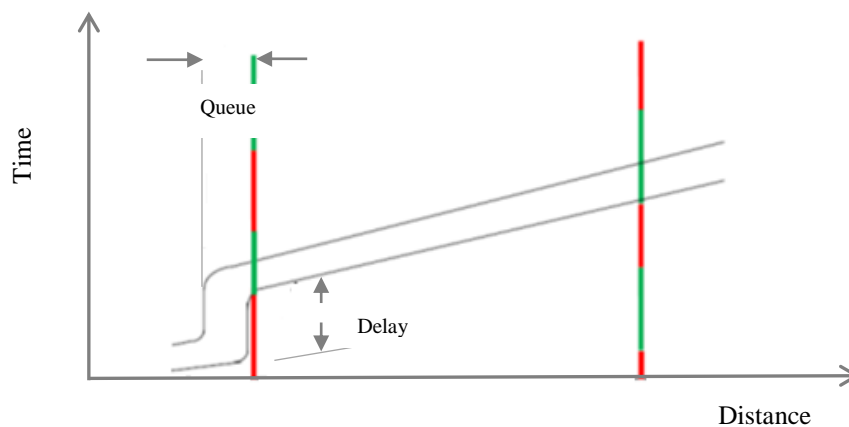
In Australia, Akçelik and Association Pty Ltd. developed a platform (aaSidra) which is an analytical software that deals with intersections based on lane by lane analysis, it is also compatible with the Highway capacity Manual HCM (TRB, 2000) and could be adapted for both right-hand traffic and left-hand traffic. aaSidra uses the HCM equations for delay and queue length for signalised intersections.

The issues of the existing models for designing the RTL length at signalised intersections were raised in a meeting with Mr David Landmark the Traffic Engineering Standards Manager and Mr Slavco Naumovski Standard Traffic Engineer at Main Road Western Australia (MRWA), as the models used now result in an estimate shorter than the required length. Sydney Coordinate Adaptive Traffic System (SCATS) was also discussed, the main feature of this system is minimising the delay and the expected queue length, which are associated with dealing with signalised intersections as isolated operation, by using

coordinate signals which allow a continuity of the green phase for motorist. Figure 2.4 illustrate the concept of coordinated signals.



a) Queue and the delay occur in the second intersection due to the uncoordinated signal timing offset



b) Queue and delay do not occur in the second intersection due to the coordinated signal timing

Figure 2.4 Effect of applying coordinated signal timing on queue and delay (source: Sydney Transport Road & Maritime Services website).

2.6 Conclusions

The literature review explains how complex the parameters involved in the estimation of the right-turn lane length are, especially in the calculation of the storage length. Several models have been developed to estimate the storage length. However, few addressed the stop and go characteristics at signalised intersections, hence, there is a need to integrate signal phase and timing when design the storage length.

Moreover, large body of literature deal with the deceleration length only in terms of the deceleration rate and the lane width, it was observed that the deceleration length calculated using simulation based method indicated inconsistent values at high speed. This could be due to the effect of pavement friction on deceleration rate at high speed., an analytical model should be investigated to include the longitudinal friction impact on deceleration rate at different speeds. In addition, the interpretation of the comfortable deceleration rate is inconsistent in the available literature. There is a need to investigate this value and compare it with other guidelines.

CHAPTER 3

ANALYTICAL MODELS FOR ESTIMATING THE DECELERATION LENGTH

3.1 General

The design of the deceleration length should be based on the performance of cars. It is not cost effective to take into consideration the trucks' performance, especially on urban roads. It is also acceptable for trucks to start deceleration in the through lane (Austroads, 2009). The length of the right-turn lane should also accommodate for the waiting vehicles in case of red arrow or when waiting for the appropriate time gap to clear the intersection.

In this chapter, the study investigates and compares two analytical models of calculating the deceleration length for the right-turn lane at signalised intersections. These models can also be used for calculating braking distance in other geometric features design. The first model relies on the assumption of a constant deceleration rate and the second model takes in account the friction coefficient between the vehicle's tyres and the pavement surface and its influence on the deceleration rate. The latter model takes in consideration the change of the deceleration rate in relation to the vehicle speed.

3.2 Analytical Formulation

In general practice, there are two models that are adapted by engineers to calculate the distance required for a vehicle to stop. The first one based on the assumption of constant deceleration rate and driven from the basic equations of motion, this model is referred to as the constant deceleration rate (CDR) model in this study, whereas the second model using the concept of the forces on rotation wheels, (Hall et al, 2009), that takes in account the force of friction generated by the braking force proportionally to the pavement coefficient of friction and is referred to as the coefficient of friction (CoF) model in the present study. Whilst the first model considers a constant value for deceleration rate assuming it is the same for all design speeds, the second model considers the variation of deceleration in relation to speed,

the type of surface and the tyres condition by using different coefficients of friction as reported by guidelines such as AASHTO (1994) and Austroads (2002) as mentioned above

The following section examines these two models and evaluate them against Austroads (2009), AASHTO (2001) and TxDOT (2006) guidelines as well as a recent simulation based method (Qi et al., 2012).

3.2.1 Constant deceleration rate model

This model driven from the well-known equations of motion by the following steps:

$$a = \frac{v_d - u}{t} \quad (3.1)$$

where

a = the deceleration rate (m/s^2),

v_d = the design speed (m/s),

u = the ending speed (m/s) = 0 in case of stopping.

By integrating the velocity with respect to time, the distance is derived as follow

$$\int_0^t v_d dt = \int_0^t (u + at) dt$$

$$S_d = ut + \frac{at^2}{2} \quad (3.2)$$

where

S_d = the deceleration length (m)

By substituting the term a from Equation. (3.1) into Equation (3.2), the following expression for the deceleration length is driven:

$$s_d = \frac{1}{2}(u + v_d)t \quad (3.3)$$

By Substituting the value of (t) from Equation (3.1) into Equation (3.3) we obtained the following equation:

$$v_d^2 - u^2 = 2as_d \quad (3.4)$$

Providing $u = 0$ when vehicles stop the following equation is concluded:

$$s_d = \frac{v_d^2}{2a} \quad (3.5)$$

The following equation is applied when v is given in km/h

$$s_d = \frac{v^2}{25.9a} \quad (3.6)$$

Two sets of the deceleration length values were calculated using Equation (3.6) for different design speeds range 50-90 km/h with increment value of 5. The first set was obtained for deceleration rate of 1.5 m/s^2 , this deceleration rate was chosen as an approximate of the deceleration rate found in some studies see section 2.3. The second set of results was calculated using deceleration rate of 2.74 m/s^2 which is recommend as a comfortable deceleration rate (SUDAS, 2006) and was used as guideline for Qi et al.(2012) investigation. These results were compared with guidelines, namely Austroads (2009), AASHTO (2001) and TxDOT (2006) guidelines in addition to a recent simulation based method (Qi et al., 2012) as mentioned before.

3.2.2 Coefficient of friction model

This model takes in consideration the longitudinal coefficient of friction which could be referred to as the coefficient of deceleration (Austroads, 2009). Based on a former American guidelines (AASHTO, 1994), it was reported that the coefficient of friction, as an indication of the skid resistance, drops when the design speed increases. The use of a constant deceleration rate regardless of the speed does not accommodate for this observable fact.

According to Hall et al.(2009), the resistive force is specified by the friction coefficient, μ_f which is the ratio of the tangential friction force (F) between the tire tread rubber and the road surface to the perpendicular force or vertical load (F_w).Figure 3.1. Hence, the following analytical formulation can be driven:

$$\begin{aligned} \mu_f &= \frac{F}{F_w} \\ &= \frac{ma}{mg} \\ \mu_f &= \frac{a}{g} \\ a &= \mu_f g \end{aligned} \quad (3.7)$$

where

μ_f = longitudinal coefficient of friction,

m = mass of the car in unit weight,

a = deceleration rate m/s^2 ,

g = gravity acceleration = 9.81 m/s^2

By substituting the value of a in Equation (3.7) into Equation (3.5) the following expression is derived

$$s_d = \frac{v^2}{2\mu_f g} \quad (3.8)$$

Similarly to the previous model

s_d is the deceleration length (m)

v is the design speed m/s

g is the gravity acceleration = 9.81 m/s^2

μ_f is the coefficient of friction

to calculate deceleration length in (m) providing the design speed given in (km/h) the equation 3.8 can be written as follow

$$s_d = \frac{v^2}{254\mu_f} \quad (3.9)$$

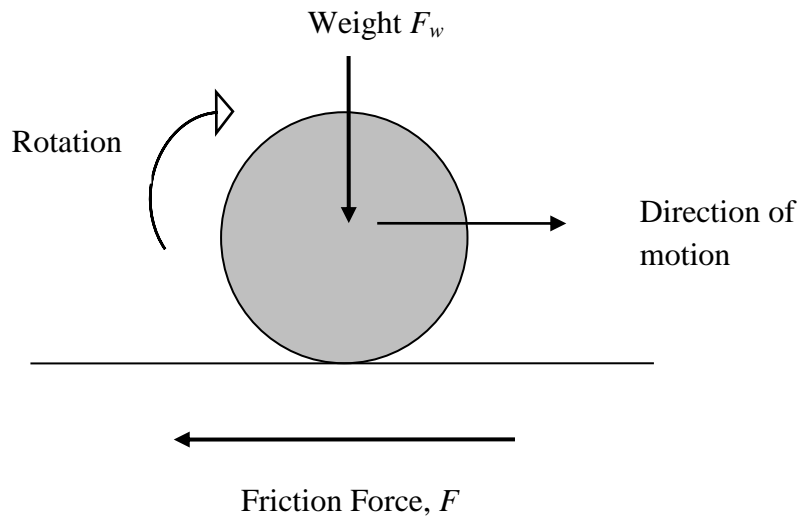


Figure 3.1 Plain illustration of forces acting on a rotating wheel (adapted from Hall et al. (2009))

As the deceleration length is inversely proportional to the longitudinal friction as implied by equation (3.8), it was rational to investigate the deceleration lengths in relation to the coefficients of friction. Using Equation (3.9), three sets of deceleration lengths were calculated for speeds range 50 km/h-110 km/h with increment of 5 km/h, applying the values of longitudinal coefficient of friction recommended by AASHTO (1994), Austroads (2002) and the constant coefficient of friction for all speeds of 0.26 suggested by Austroads(2009).

3.3 Analysis and Discussion

In the next section, the two previous models were investigated and the results were compared with the aforementioned guidelines and study. The comparisons were presented in two graphs. The first graph compares the deceleration length values resulted from the CDR model for two values of deceleration rate (1.5 m/s^2 and 2.74 m/s^2).Figure 3.2.

The second graph compares the deceleration length derived from the CoF model taking in consideration the coefficient of friction factors suggested by the the three previously mentioned guidelines, AASHTO (1994), Austroads (2002) and Austroads (2009) Figure 3.3.

3.3.1 Constant deceleration rate model analysis

The deceleration length were calculated, using Equation 3.6, for two values of deceleration rate; 1.5 m/s^2 and 2.74 m/s^2 and compared with the aforementioned guidelines.

A deceleration rate of 1.5 m/s^2 yield variation of less than 9% comparing to that of AASHTO (2001) for speed of 50 and 60 km/h, however the variation was much closer, less than 3%, for speed more than 60 km/h. Comparing the results to the simulation method Qi et al.(2012) shows a significant disparity ranged 23 % - 49%, the ratio of the variation increases when the speed increases. It is also noted that the other guidelines such as TxDOT (2006) and Austroads (2009) recommended much lesser values for deceleration length. Figure 3.2.

A deceleration rate of 2.74 m/s^2 provided comparable figures to that of the recommended values by Austroads, which is justified since Austroads states clearly that the comfortable deceleration rate for estimating the deceleration length is 2.5 m/s^2 . Also the deceleration lengths were to a considerable degree less than the corresponding deceleration lengths provided by TxDOT (2006) and the Qi et al. simulation (2012). Figure 3.2.

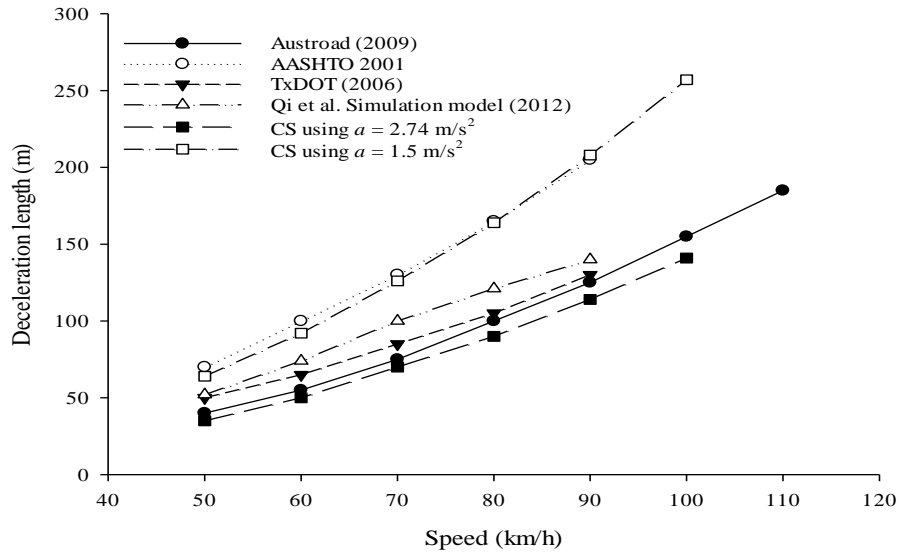


Figure 3.2 Comparison of the estimated deceleration lengths by the current study(CS) constant deceleration rate model.

3.3.2 Coefficient of friction model analysis

Using Equation 3.9, three sets of deceleration length values for different design speeds have been calculated, the first set corresponds to the friction coefficients provided by Austroad (2002) Table 3.1, the second set uses the coefficients of friction reported in AASHTO (1994) Table 3.1 and the third set has been calculated for a coefficient of friction of 0.26 as recommended by Austroads (2009). These deceleration lengths were compared to the same guidelines as in section 3.3.

Applying the coefficient of friction values provided by Austroad (2002) yield significant lower figures comparing with other guidelines

On the other hand, applying the coefficients of friction suggested by AASHTO (1994) resulted in deceleration lengths which are relatively closer but less to that of the other guidelines and study. Figure 3.3

On another note, the coefficients of friction applied by AASHTO (1994) correspond to deceleration rate range between 3.924 m/s^2 and 2.7468 m/s^2 , for design speed between 30 km/h and 110km/h. The following guidelines AASHTO (2001, 2004). apply deceleration rate of 3.4 m/s^2 to calculate the braking distance for all design speeds.

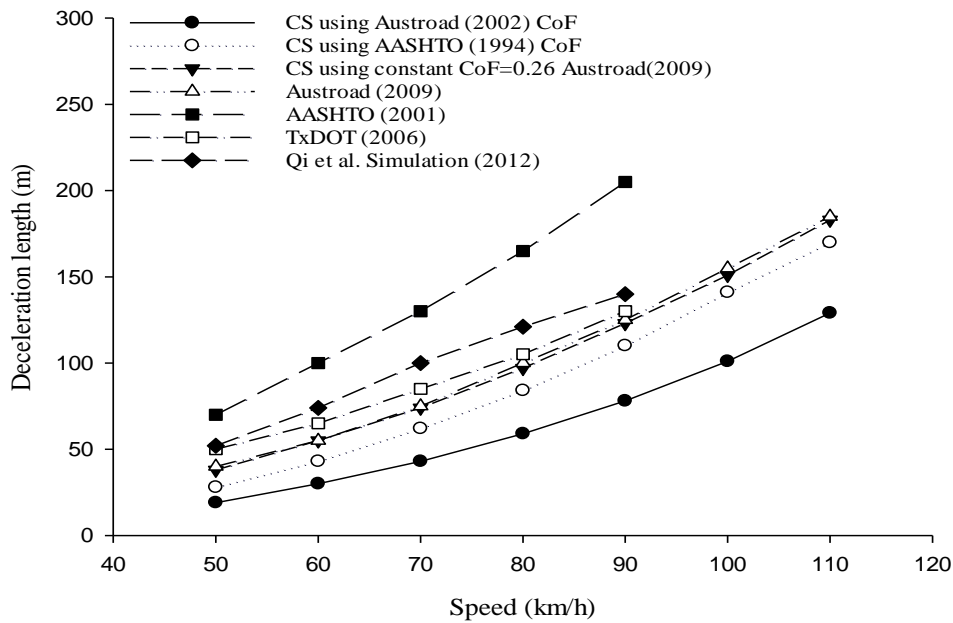


Figure 3.3 Comparison of the estimated deceleration lengths by the current study(CS) Coefficient of friction (CoF) model

It is notable that the reaction of the driver will not cause the car to stop within the available distance unless the pavement surface is capable of generating enough friction force to stop the car, for that reason AASHTO guidelines (2004) discard the value of 4.5 m/s^2 that was noted by Fambro et al (1997) as it is not applicable for most wet pavement to provide the corresponding coefficient of friction of 0.46. Meanwhile design the turn lane pavement with a particular coefficient of friction could be utilise to reduce the deceleration length if physical constraints are presented assuming that calculating deceleration length in turn lane abides by the same principles to that of calculating breaking distance in any other roads geometric features.

Table 3.1. Longitudinal coefficients of friction values for different design speeds (Source: AASHTO 1994, Austroads, 2002)

Design Speed km/h	AASHTO (1994)	Australia Guidelines (2002)
30	0.4	-
40	0.38	0.56
50	0.35	0.52
60	0.33	0.48
70	0.31	0.45
80	0.3	0.43
90	0.3	0.41
100	0.29	0.39
110	0.28	0.37

3.3.3 The impact of changing the coefficient of friction on deceleration length

The present study investigates the impact of the friction demands of the pavement on deceleration length. It is logical that the coefficient of friction model will provide a realistic approach to calculate the deceleration length for various design speed by incorporate the pavement design to assist in the geometric plan especially when the layout is restricted by physical feature.

Figure 3.4 depicted the relationship between deceleration lengths at different speeds for low, medium and high friction treatments of coefficients of friction of 0.28, 0.4 and 0.5 respectively, Applying a higher coefficient of friction will reduce the deceleration length considerably, when increase the coefficient from 0.28 to 0.4 the required deceleration length could be reduced by 30%. A reduction of 44% was calculated if a coefficient of friction of 0.5 is used, however based on AASHTO recommendation this increase is not applicable in wet pavement (see section 3.3.2). The design of the RTL pavement to produce high coefficient of friction can be employed to reduce the deceleration when the space is limited

However further studies are needed to evaluate the impact of using pavement of high coefficient of friction on the departure rate of the turning vehicles.

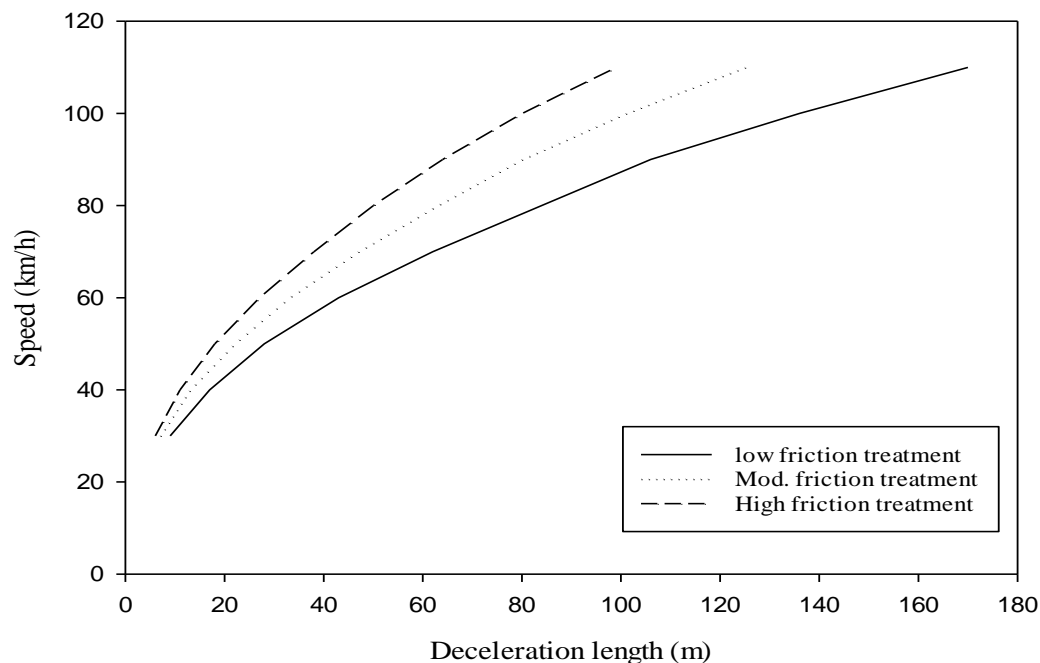


Figure 3.4 Variation of deceleration length, speed and friction treatment applying the coefficient of friction model.

3.4 Conclusions

In this Chapter, the methods of calculating the right-turn deceleration length were examined. Two analytical models were discussed and evaluated in comparison with other guidelines and studies specifically, Austroads (2009), TxDOT (2006), AASHTO (2001) and Qi et al. (2012). The comparison between the CDR model using a deceleration rate of 2.74 m/s^2 showed comparable figures to that of Austroads (2009), TxDOT (2006), and Qi et al. (2012). By applying a deceleration rate of 1.5 m/s^2 , the CDR model resulted in very close figures to that of the AASHTO (2001) recommended values.

On the other hand the CoF model's results were significantly low when applying the CoF suggested by previous Australian guidelines (2002). Whereas the results were similar when applying the CoF recommended by AASHTO (1994). Higher coefficient of friction

decrease the deceleration length considerably, e.g. when increase the coefficient from 0.28 to 0.4, a reduction of 30% were estimated.

Changing the structural design for the road and the pavement skid resistance, defined by the coefficient of friction, can be employed to control the deceleration length especially when physical demand of the road does not allow for the required deceleration length. However, there is a need to investigate the impact of the pavement friction demands on the departure rate of the vehicles in the right turn lane and its influence on the queue length consequently the storage length.

It is recommended to use the CoF model; since it has the advantage of incorporating the pavement condition into the geometric design of the right-turn lane deceleration length.

CHAPTER 4

SIMULATION MODEL FOR ESTIMATING STORAGE LENGTH

4.1 General

Many simulation models have been developed to estimate the right-turn storage length at signalised intersections, however the existing simulation based software is either time consuming or lacking in accuracy (Qi et al., 2012). Moreover, although several methods have been developed to estimate the storage length, there have been few attempts to provide a flexible model to integrate signal phases and timings into the design of the right turn-lane storage length.

In this study, a simplified simulation model, in which all signal phases and types are integrated, has been developed for the left-hand traffic. It is also applicable to right-hand traffic countries.

4.2 Simulation Model Description

The simulation model represents the situation in which cars arrive at a set of traffic light with the option of continuing through, or turning right. There is only one lane of traffic approaching the intersection which branches into a through lane and a tuning lane. The traffic signals operate on a fixed time/periodic sequence, and can allow for both permissive and protected right-turn signal flow. Any vehicles left in the queue when the traffic light turns red remain in the system ready to depart during the next green phase.

4.2.1 Model assumptions

1. Traffic is assumed to arrive randomly, and is modelled using a Weibull distribution with shape parameter equal to one. Traffic in the opposing direction is also assumed to arrive randomly, and is allowed to have a different mean rate of arrival.
2. Under green light conditions it is assumed that the traffic departs from the intersection at a constant rate. The departure rate is based on an average value of the time taken

for cars to react to the movement of the car in front, and to travel the length of the queue.

3. When the traffic light turns green the first car is assumed to move off immediately without hesitation; however, if the traffic lights change to a permissive phase the first car will be delayed by a fixed amount of time. This delay is introduced to reflect the time taken for a permissively turning vehicle to assess whether it is safe to turn.
4. Although there is no explicit consideration of left-turning traffic, it is assumed that left-turning traffic is subject to the same signal constraints as the through traffic. The length of the turning lane can be expressed in terms of a number of vehicles (vehicles are assumed to have a common length).
5. The model calculates the appropriate length of the right-turn lane for avoiding the overflow and the blockage situation in 95% of the cycles.

4.2.2 Model algorithm

The overall structure of the simulation model is illustrated in Figure 4.1. Once the system and state parameters have been initialised, the simulation algorithm defines a next event vector. The next event vector has four entries, each corresponding to a specific type of event that will change the state of the system: 1. A new vehicle arrival; 2. A vehicle departure from the through lane; 3. A vehicle departure from the right-turn lane; 4. A change in the traffic light signals. The entries in the next event vector represent the next time at which each of the above events will occur. The minimum time value in the next event vector indicates the next event, and is labelled '*Now*'. Once the next event vector is defined, the next event is identified (i.e. the event with the minimum next time value), and the system is updated accordingly. If the maximum simulation duration '*t_{max}*' has not been exceeded then the simulation algorithm returns to update the next event vector, and the cycle continues. Once the maximum simulation duration is exceeded, the simulation terminates. See appendixes A and B.

4.2.3 Model inputs

The model inputs are identified below:

- The peak approach traffic volume as number of vehicle per hour per lane (vphpl)
- The phase type and timing concluded as a matrix (configuration matrix) containing the sequence of operational states of the intersection. Each column specifies a state in

which the first row indicates whether the signal for the through lane is red (=0) or green (=1), the second row indicates whether the turning light is red, green or permissive (=2), and the bottom row indicates the state durations shown in the matrix sample below

0	0	1	1	Through lane signal type
0	1	0	2	Right-turn lane signal type
t_1	t_2	t_3	t_4	Phase timing

- The turning probability of the approach traffic volume

These inputs are used to design the RTL length to avoid the overflow and the blockage situations in 95% of the cycles. Thus, the RTL length is the 95th percentile of the through lane queue when the blockage is the limiting factor while the RTL length is the 95th percentile of the turning lane queue when the overflow is the restraining factor. This model could be used to evaluate the traffic operation at a certain intersection by inputting the existing RTL length as number of vehicle.

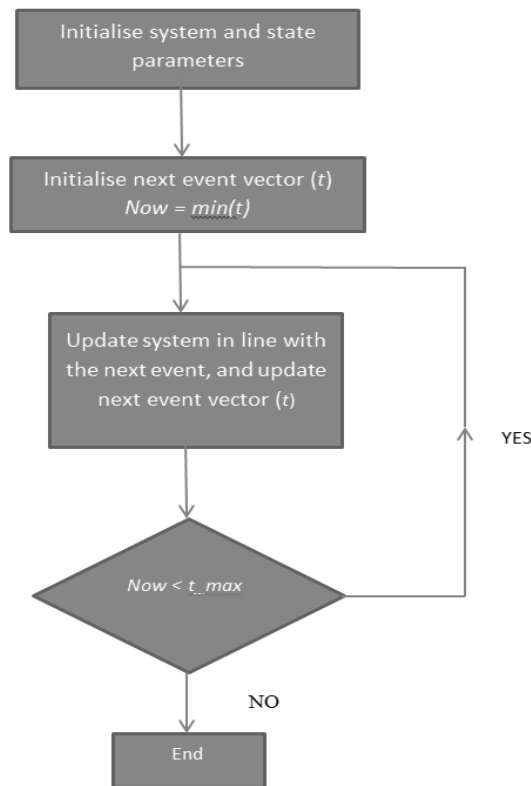


Figure 4.1 Framework of the Simulation Model

4.3 The Procedure for Comparing the Simulation Results Against the Analytical Model

The simulation model was run to estimate the right-turn lane length such that the blockage and the overflow are avoided in at least 95% of cycles. The simulation was tested for five different phase configurations under two different cycle lengths of 90 s and 120 s. The results were obtained for the turn probability values of 30%, 50% and 70%, and compared with the corresponding results from the analytical method by Kikuchi and Kronprasert (2010). The right-turn lane (RTL) lengths were examined for approaching traffic volumes of 200, 400, 600, 800 (vphpl) and was recorded in number of vehicles (veh) (Table 4.1). The phase timings are similar to the suggested values by Kikuchi and Kronprasert (2010), for the purpose of comparison and validation. These values were entered into configuration matrix as explained in the following subsection.

4.3.1 Phase type and timing configuration matrix presentation

- Configuration Matrix in cycle for 90 s cycle

Split Phase Phase

$$\begin{bmatrix} 0 & 1 \\ 0 & 1 \\ 68 & 22 \end{bmatrix}$$

PmO Phase

$$\begin{bmatrix} 0 & 1 \\ 0 & 2 \\ 45 & 45 \end{bmatrix}$$

PO Leading Phase

30% turning probability

$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 17 & 28 & 45 \end{bmatrix}$$

50% turning probability

$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 21 & 24 & 45 \end{bmatrix}$$

70% turning probability

$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 25 & 20 & 45 \end{bmatrix}$$

PO lagging Phase

30% turning probability

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 28 & 17 & 45 \end{bmatrix}$$

50% turning probability

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 24 & 21 & 45 \end{bmatrix}$$

70% turning probability

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 20 & 25 & 45 \end{bmatrix}$$

PPRT Phase

30% turning probability

$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & 2 & 0 \\ 20 & 25 & 45 \end{bmatrix}$$

50% turning probability

$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & 2 & 0 \\ 26 & 19 & 45 \end{bmatrix}$$

70% turning probability

$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & 2 & 0 \\ 30 & 15 & 45 \end{bmatrix}$$

- Configuration Matrix for 120 s cycle

Split Phase

$$\begin{bmatrix} 0 & 1 \\ 0 & 1 \\ 90 & 30 \end{bmatrix}$$

PmO Phase

$$\begin{bmatrix} 0 & 1 \\ 0 & 2 \\ 60 & 60 \end{bmatrix}$$

PO Leading Phase

30% turning probability

$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 25 & 35 & 60 \end{bmatrix}$$

50% turning probability

$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 30 & 30 & 60 \end{bmatrix}$$

70% turning probability

$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 40 & 20 & 60 \end{bmatrix}$$

PO Lagging Phase

30% turning probability

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 35 & 25 & 60 \end{bmatrix}$$

50% turning probability

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 30 & 30 & 60 \end{bmatrix}$$

70% turning probability

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 20 & 40 & 60 \end{bmatrix}$$

PPRT Phase

30% turning probability

$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & 2 & 0 \\ 20 & 40 & 60 \end{bmatrix}$$

50% turning probability

$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & 2 & 0 \\ 27 & 33 & 60 \end{bmatrix}$$

70% turning probability

$$\begin{bmatrix} 0 & 1 & 0 \\ 1 & 2 & 0 \\ 35 & 25 & 60 \end{bmatrix}$$

The model simulates each approach separately so it could be used in a T intersection as well as the typical signalised intersections.

4.4 Results and Discussion

The comparison between the Kikuchi and Kronprasert analytical model (KA) and the current simulation study (CS) is presented in Figures 4.2 and 4.3 and Table 4.1

The simulation results were consistent with the corresponding results from the analytical method and indicated similar trends and values in most cases for the split phase, PO and PmO in the 90 s cycle as shown in Figures 4.2 (a-c, f-g) and the split phase, PO, PmO and PPRT in the 120 s cycle as shown in Figure 4.3. However in the protected leading and lagging phase, the simulation results at 70% probability of right-turn traffic show a difference of up to 15% in comparison with the KA results that were obtained at a lower probability of right-turn traffic as illustrated in Figures 4.2 (b-c), and Figures 4.3(b-c). This could be due to the analytical method's limitation in capturing the dynamic interaction between cars (Qi et al., 2012). This interaction has more impact in high traffic volumes.

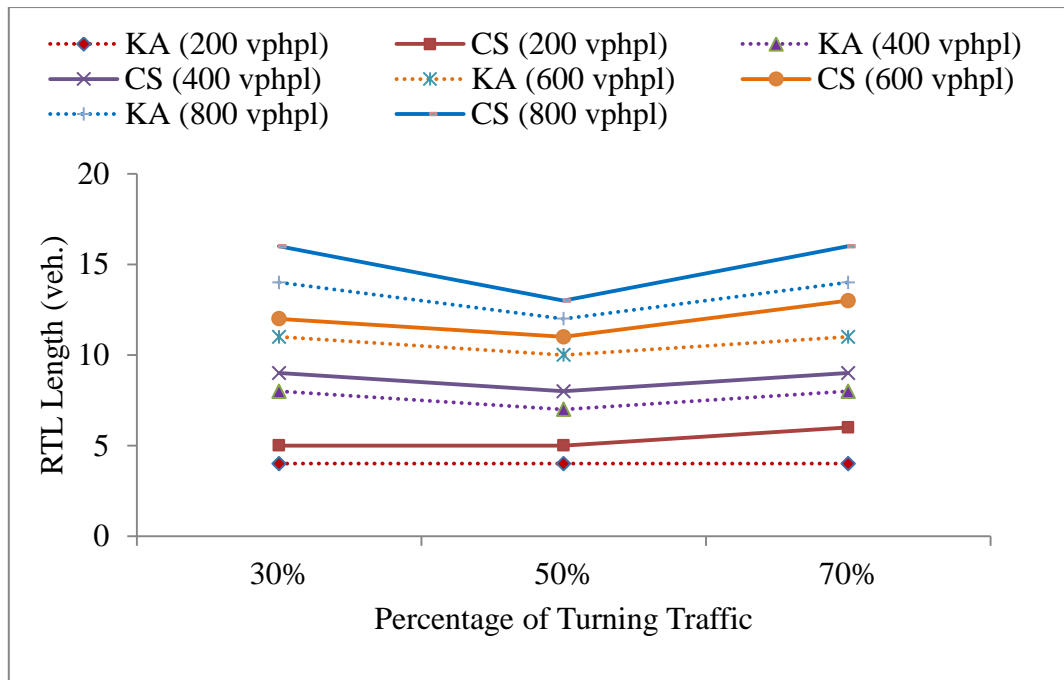
The simulation results for the PPRT phase, in the 90 s cycle Figures 4.2 (d-e), show a slight decline in the estimated values when the percentage of the turning traffic was increases, this is justified by the fact that in the PPRT phase the nature of the problem is due to blockage rather than overflow. When the right-turn traffic percentage increases, the traffic in the through lane decreases and the blockage risk declines, hence less length is needed. A similar trend was obtained with the KA method for the PPRT phase in the 120 s cycle (Figures 4.3(d-e)).

The simulation model estimates slightly longer right turn-lane lengths in the PmO and PPRT phases; thus agreeing with the finding from Kikuchi and Kronprasert study (2010) in which VISSIM software was used to validate the analytical model as blockage of up to 10% were observed in the PmO and PPRT phases, indicating underestimation of the lengths in these cases.

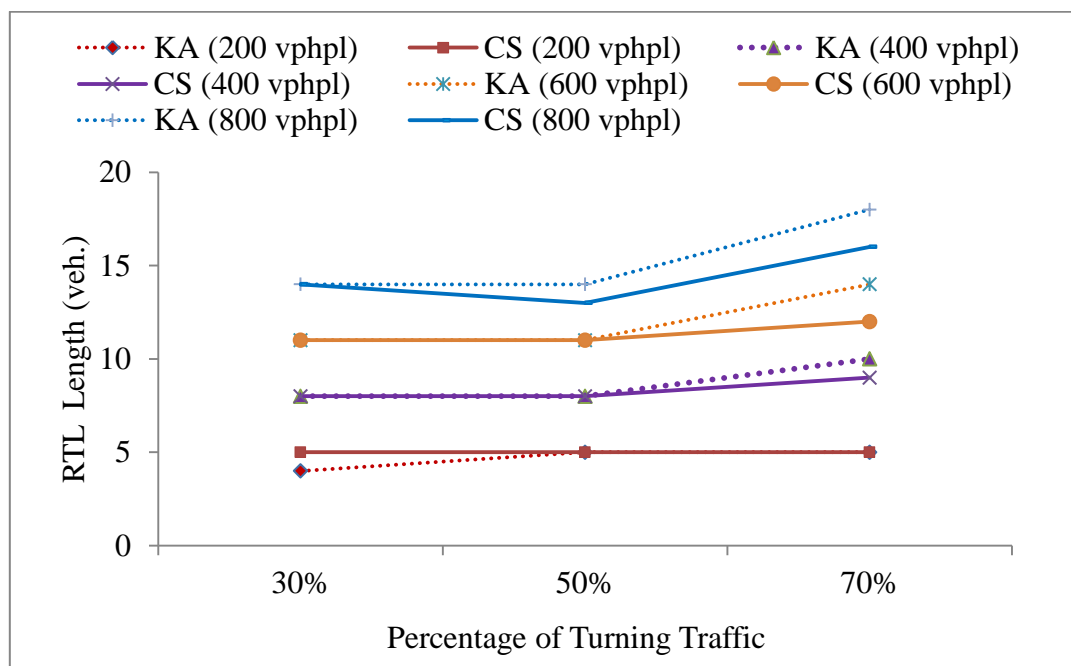
The simulation results agree with the finding of Kikuchi and Kronprasert (2010), that the volume of the opposing traffic does not affect the length required for the right-turn lane particularly when the turning traffic volume is small (see Table 4.1).

While the analytical model shows a slight shorter right-turn lane length in case of the protected leading phase than the one required in case of the lagging phase, the simulation results do not show any significant difference.

In general, shorter lengths were required for the 90 s cycle compared to the 120 s cycle in agreement with the analytical method (see Table 4.1). This could be due to the more frequent dissipation of the queues when a shorter cycle period is used.

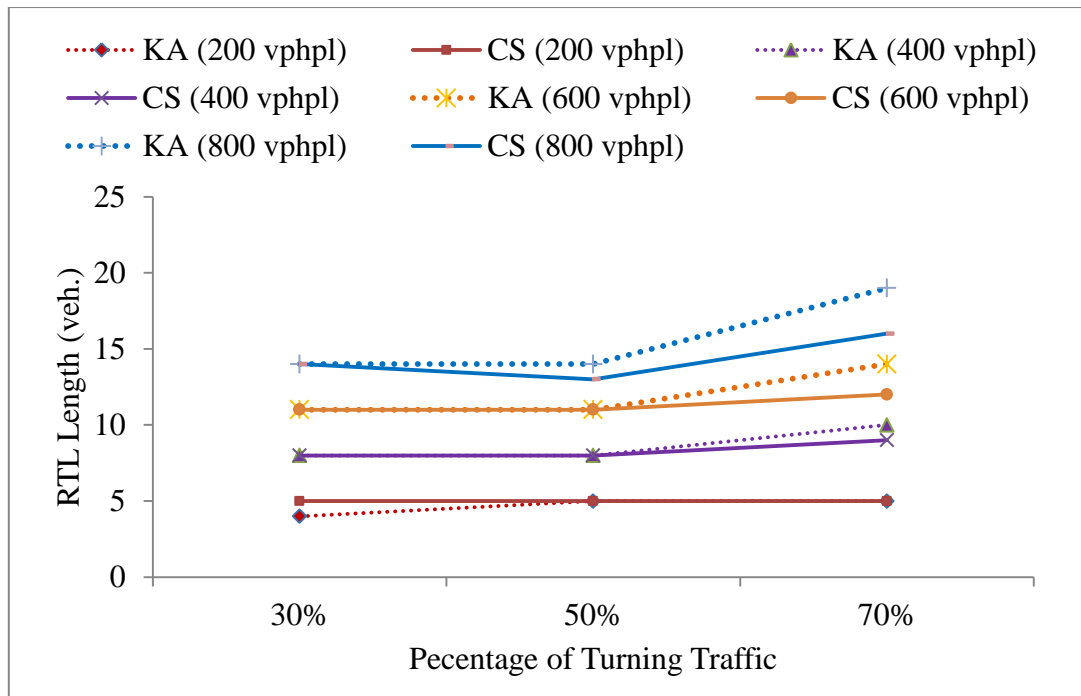


a) Split Phase

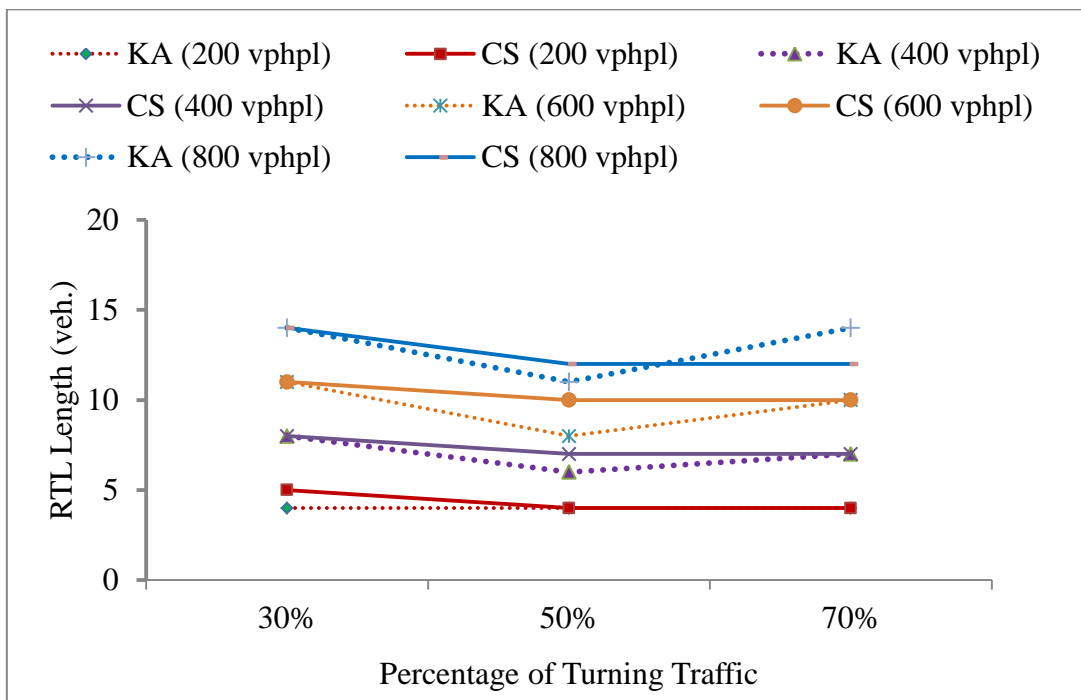


b) PO-Leading Phase

Figure 4.2 Comparison of the estimated RTL lengths by Kikuchi analytical model (KA) and the corresponding results obtained by the current simulation model (CS) cycle 90 s for different phase types



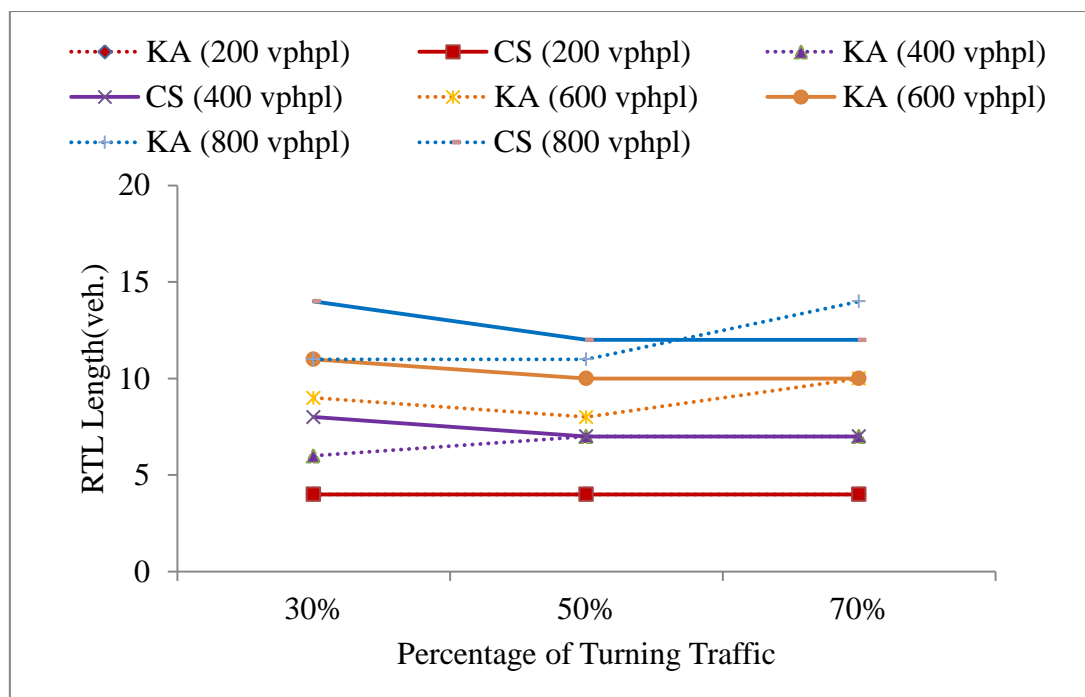
c) PO-Lagging Phase



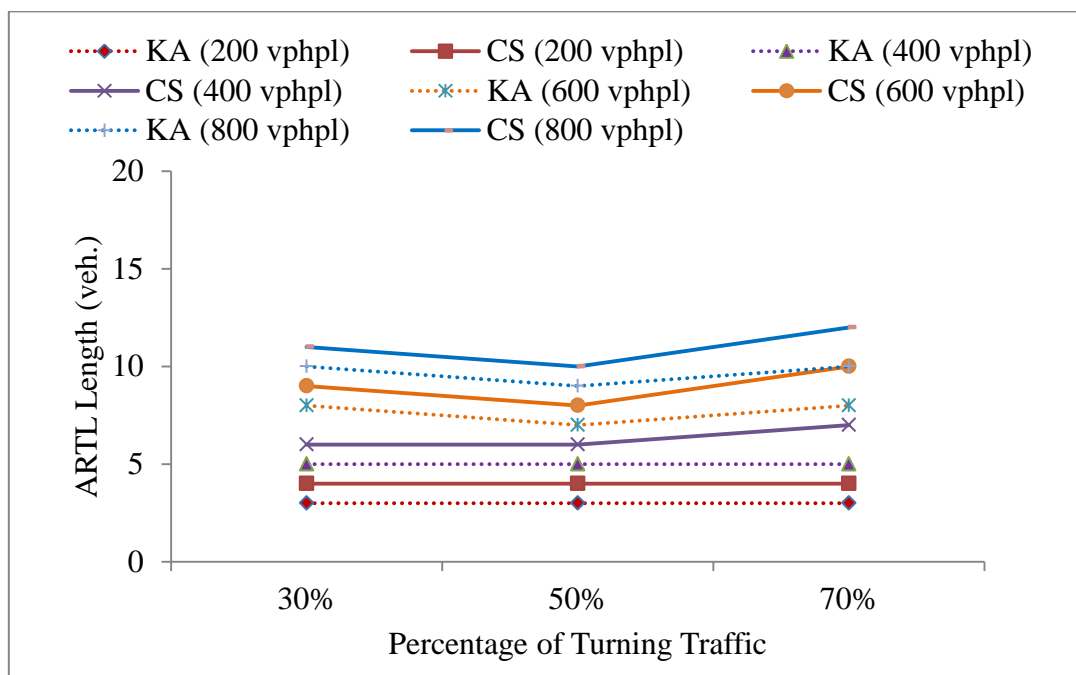
d) PPRT Phase

Opposite Traffic Volume = 200 vphpl

Figure 4.2 Continued

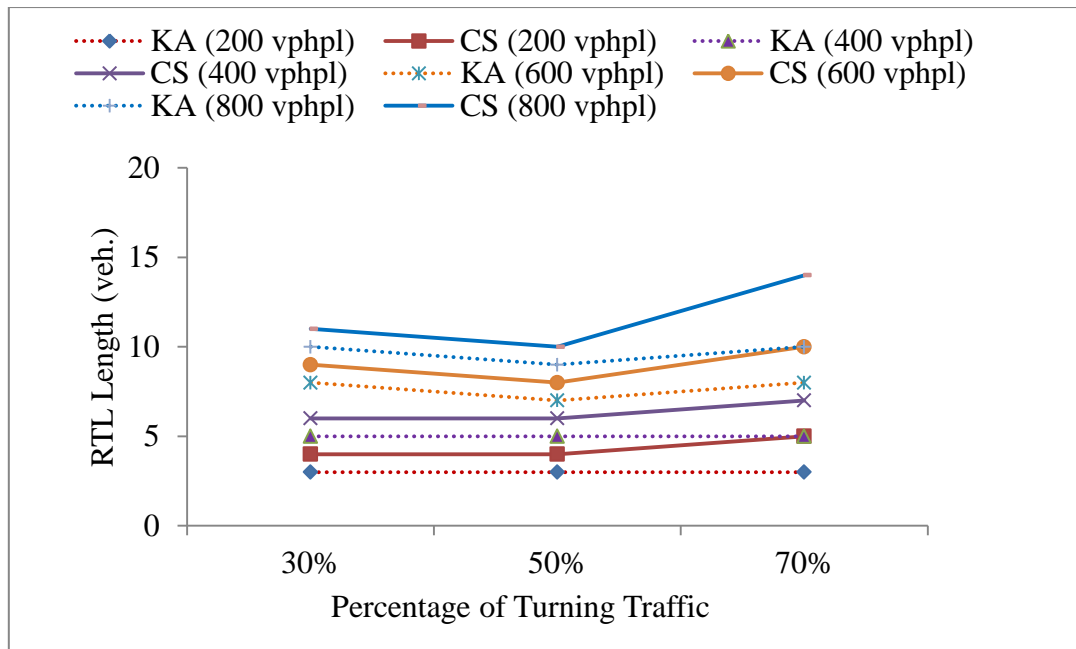


e) PPRT Phase
Opposite Traffic Volume = 600 vphpl



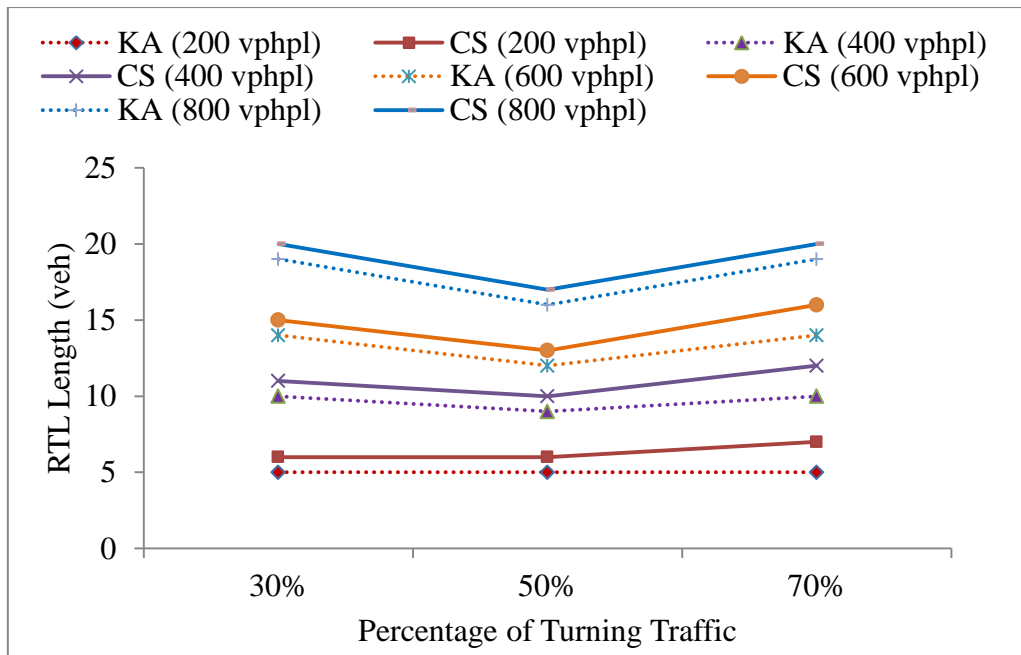
f) PmO Phase
Opposing Traffic Volume = 200 vphpl

Figure 4.2 Continued

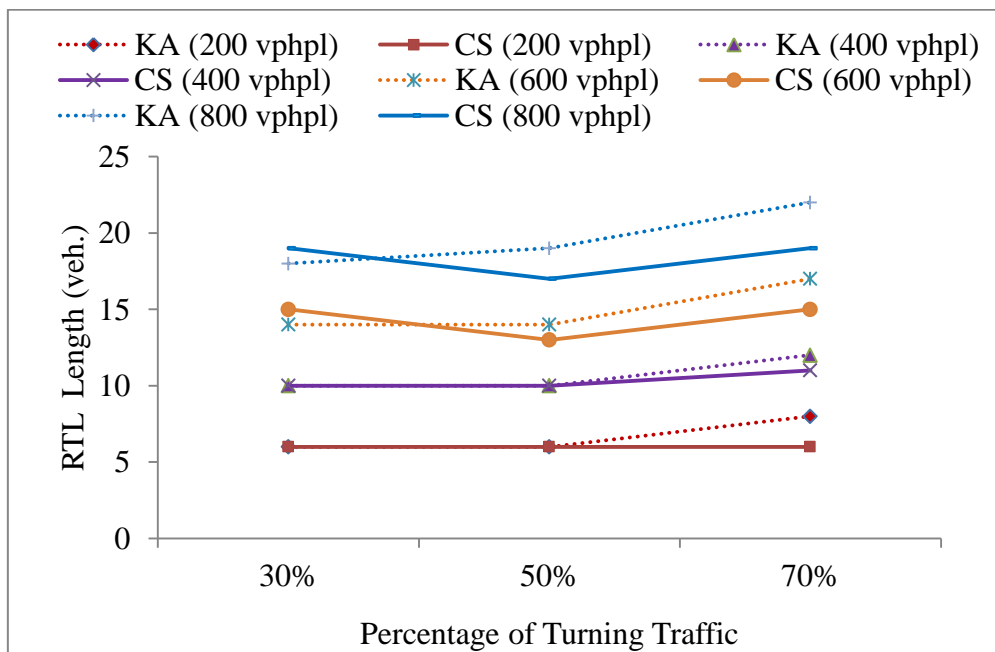


g) PmO Phase
Opposing Traffic Volume = 600 vphpl

Figure 4.2 Continued

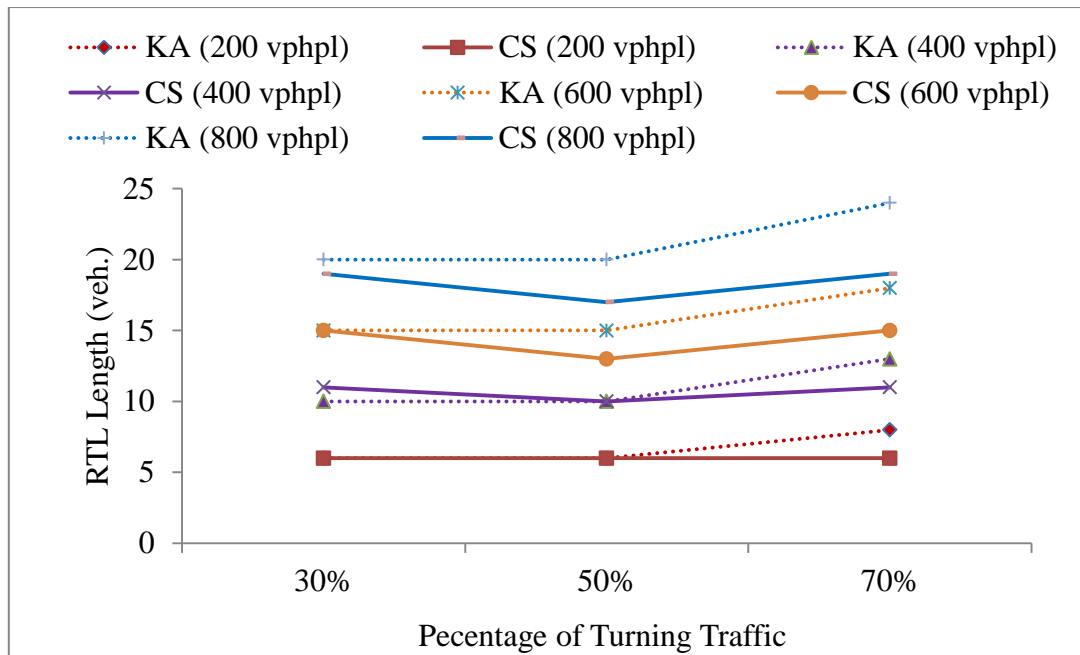


a) Split Phase

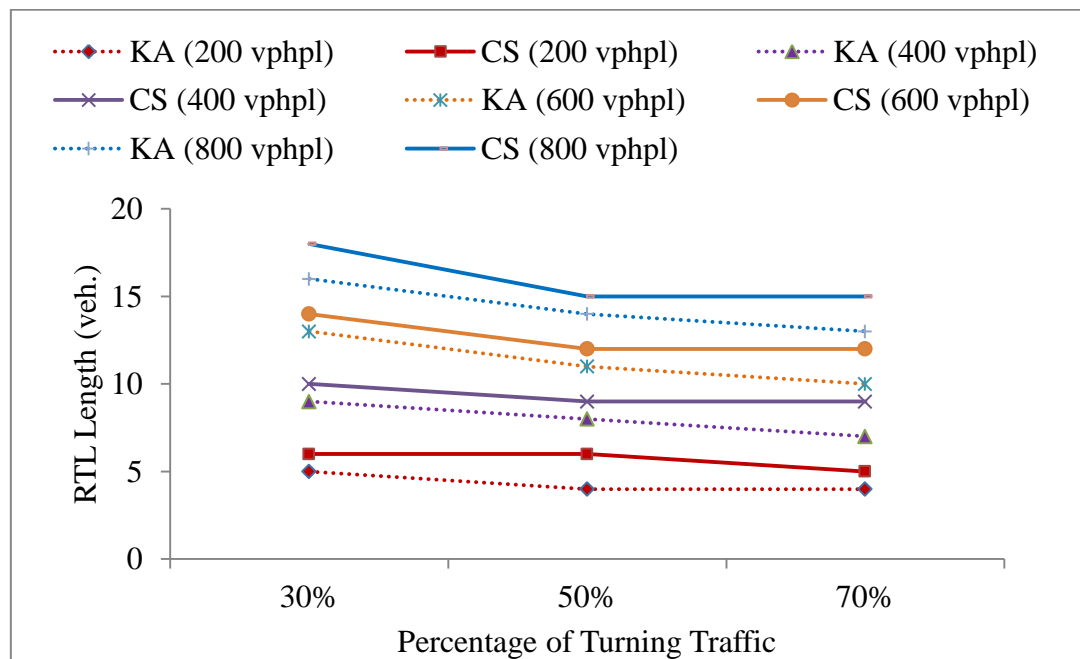


b) PO-Leading Phase

Figure 4.3 Comparison of the estimated RTL lengths by Kikuchi analytical model (KA) and the corresponding results obtained by the current simulation model (CS) cycle 120 s. for different phase types



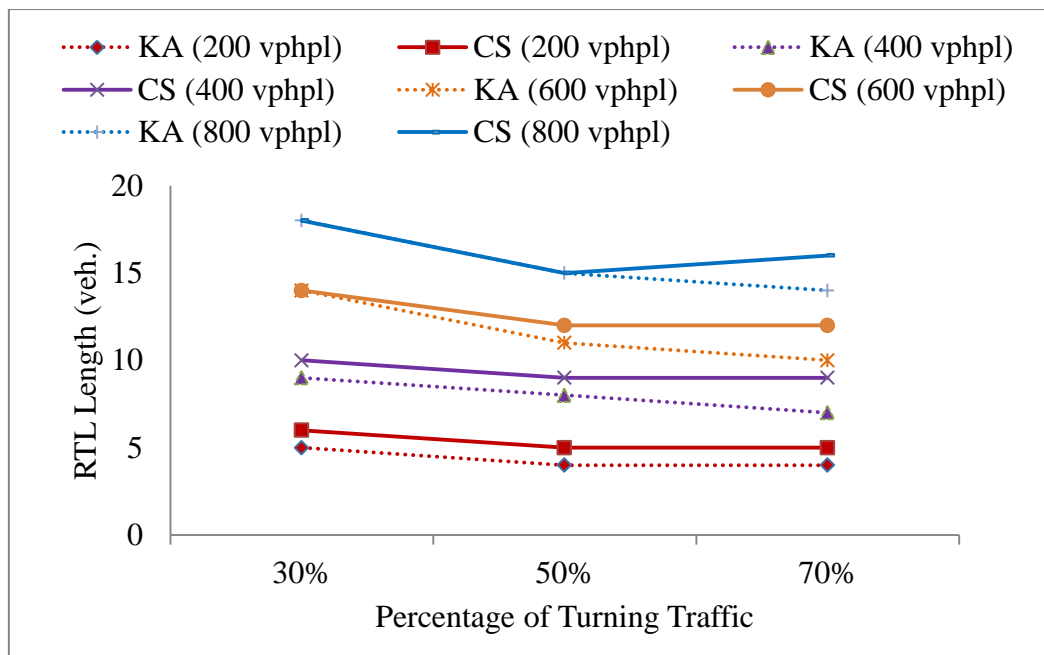
c) PO-Lagging Phase



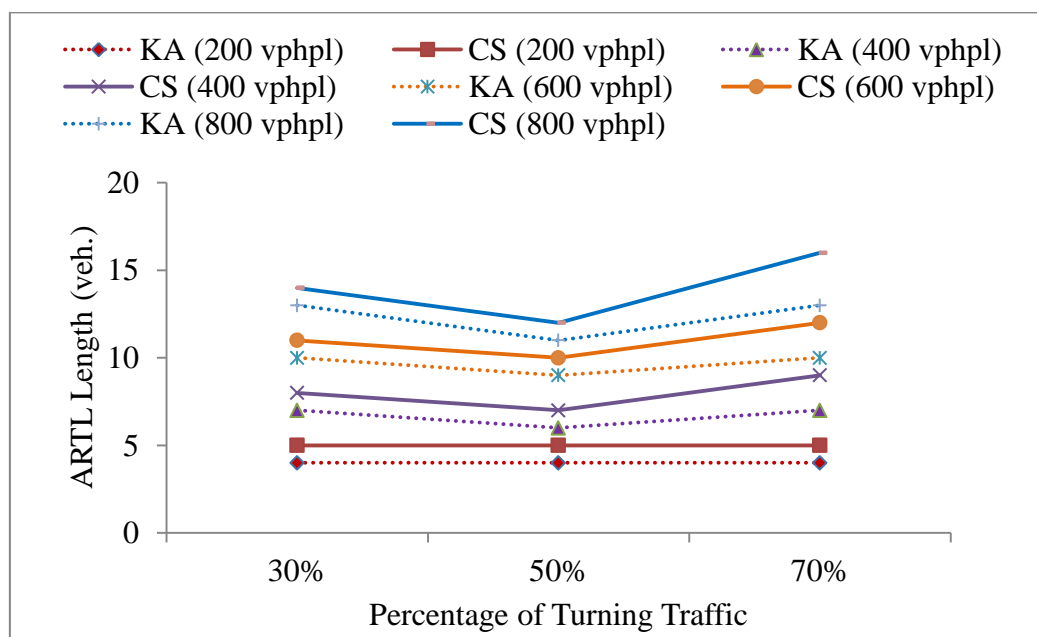
d) PPRT Phase

Opposite Traffic Volume = 200 vphpl

Figure 4.3 Continued

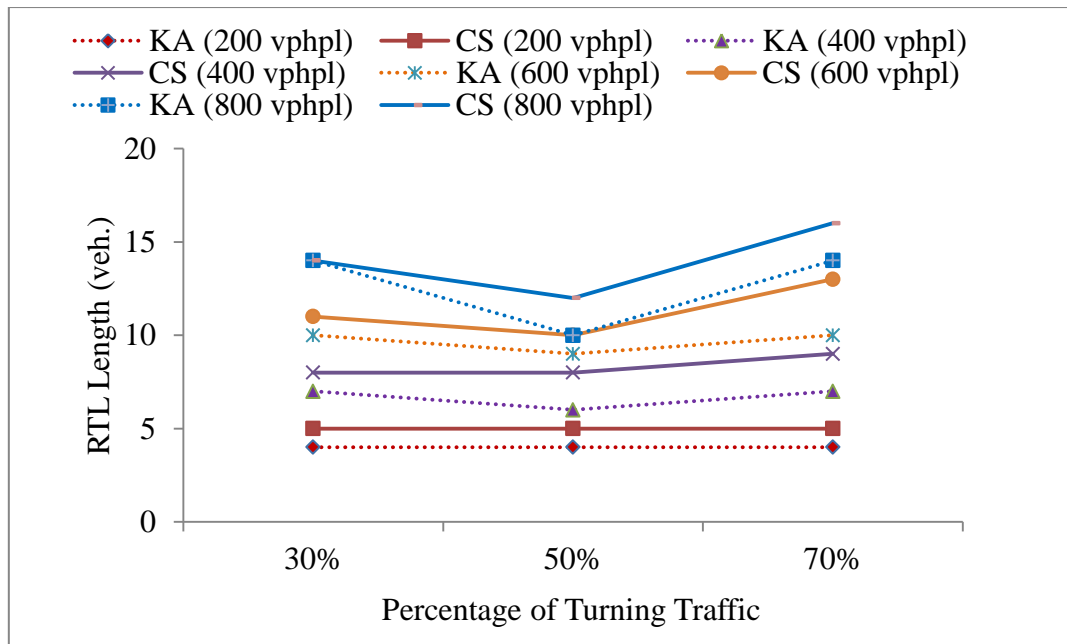


e) PPRT Phase
Opposite Traffic Volume = 600 vphp



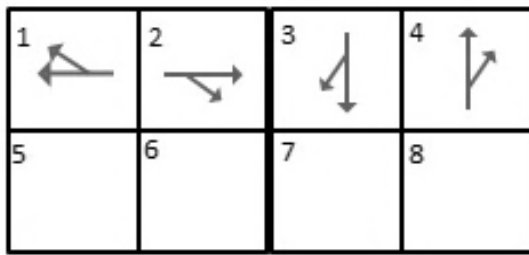
f) PmO Phase
Opposing Traffic Volume = 200 vphpl

Figure 4.3 Continued

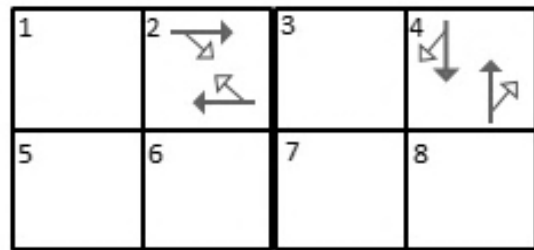


g) PmO Phase
Opposing Traffic Volume = 600 vphpl

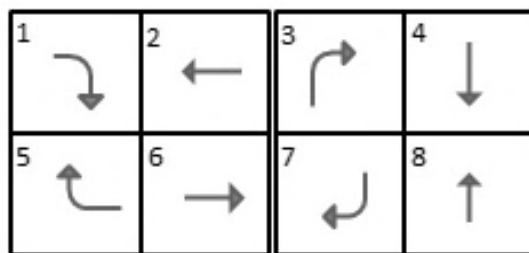
Figure 4.3 Continued



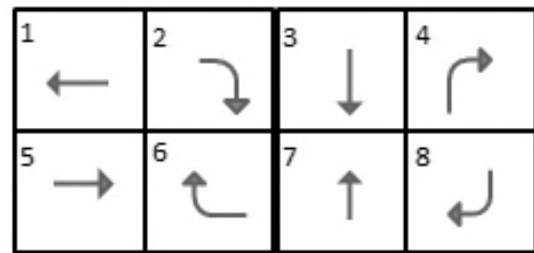
a) Split Phase



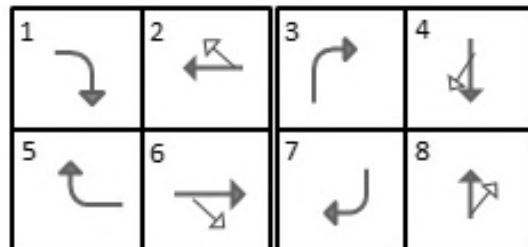
b) PmO Phase



c) PO Leading Phase



d) PO Lagging Phase



e) PPRT Phase



Protective Phase



Permissive Phase

Figure 4.4 Illustration of the different signal schemes of the right-turn phasing in typical intersection (Adapted from FHWA, 2004)

Table 4.1. Recommended RTL length in number of vehicles for Kikuchi analytical model (KA) and the corresponding results obtained by the current simulation model (CS) to avoid overflow and blockage in 95% of cycles

		Right-Turn Signal Phase Type													
Approach		Protected Phase						PPRT Phase				Permissive only			
Volume (vphpl)	Split phase						Opposing Traffic Volume				Opposing Traffic Volume				
			Leading RTL		Lagging RTL		200 vphpl		600 vphpl		200 vphpl		600 vphpl		
	KA	CS	KA	CS	KA	CS	KA	CS	KA	CS	KA	CS	KA	CS	
Cycle length 90 s, percentage of right turn volume =30%															
200	4	5	4	5	4	5	4	5	4	4	3	4	3	4	
400	8	9	8	8	8	8	8	8	6	8	5	6	5	6	
600	11	12	11	11	11	11	11	11	9	11	8	9	8	9	
800	14	16	14	14	14	14	14	14	11	14	10	11	10	11	
Cycle length 90 s, percentage of right –turn volume =50%															
200	4	5	5	5	5	5	4	4	4	4	3	4	3	4	
400	7	8	8	8	8	8	6	7	6	7	5	6	5	6	
600	10	11	11	11	11	11	8	10	8	10	7	8	7	8	
800	12	13	14	13	14	13	11	12	11	12	9	10	9	10	
Cycle length 90 s, percentage of right–turn volume =70%															
200	4	6	5	5	5	5	4	4	4	4	3	4	3	5	
400	8	9	10	9	10	9	7	7	7	7	5	7	5	7	
600	11	13	14	12	14	12	10	10	10	10	8	10	8	10	
800	14	16	18	16	19	16	14	12	14	12	10	12	10	14	
Cycle length 120 s, percentage of right-turn volume =30%															
200	5	6	6	6	6	6	5	6	5	6	4	5	4	5	
400	10	11	10	10	10	11	9	10	9	10	7	8	7	8	
600	14	15	14	15	15	15	13	14	14	14	10	11	10	11	
800	19	20	18	19	20	19	16	18	18	18	13	14	14	14	
Cycle length 120 s, percentage of right–turn volume =50%															
200	5	6	6	6	6	6	4	6	4	5	4	5	4	5	
400	9	10	10	10	10	10	8	9	8	9	6	7	6	8	
600	12	13	14	13	15	13	11	12	11	12	9	10	9	10	
800	16	17	19	17	20	17	14	15	15	15	11	12	12	12	
Cycle length 120 s, percentage of right–turn volume =70%															
200	5	7	8	6	8	6	4	5	4	5	4	5	4	5	
400	10	12	12	11	13	11	7	9	7	9	7	9	7	9	
600	14	16	17	15	18	15	10	12	10	12	10	12	10	13	
800	19	20	22	19	24	19	13	15	14	16	13	16	14	16	

4.5 Conclusions

The presented simulation model was developed to estimate the storage length at signalised intersections for different phase types by taking in consideration the left-over queue that may not be dissipated during the green time in the previous cycle. It also calculates the storage length to avoid the problems associated with the overflow and/or blockage of the right-turn lane in 95% of cycles for different approach and turn lane traffic volumes. The model considers the opposing traffic volumes in case of PPRT and PmO phases.

The model provides a flexible solution for estimating the right-turn lane length under different types and timings of phases. This can be adapted to integrate the signal phase and timings in the design when the right-turn lane length cannot be extended due to physical constraints.

For the purpose of validation comparison against Kikuchi and Kronprasert's analytical model (2010), the model uses similar parameters to that of the analytical model. The comparison showed comparable results in many cases. The storage lengths were slightly higher than the analytical model estimation in most of signal phase types, which is consistent with the limitation of the analytical model not considering leftover queues. In the protected leading and lagging phases the simulation suggested shorter right-turn lane lengths when the right-turn-lane traffic volume is high.

The next step is to use the simulation model to investigate the most appropriate signal timing in circumstances where the traffic density differs greatly between two opposing directions (e.g. at peak hour times). See Chapter 6.

CHAPTER 5

VALIDATION OF THE SIMULATION MODEL USING FIELD DATA

5.1 General

The simulation model developed in Chapter 4 for calculating the RTL length and integrating signal phase type and timing was validated and compared against an endorsed analytical model and the results were consistent, however, comparison against real data was vital to confirm the model validity. This Chapter outlines the data collection plan, methods of collection and calculation of the simulation model inputs and the required outputs parameters for validation.

5.2 Data Collection Plan

A data collection plan was developed to ensure that all the data needed for validating the model (Chapter 4) was identified and collected. The data collection plan addresses the following issues:

- Selection of intersections and the subject approaching bound/direction;
- Identification of the data needed to validate the simulation model;
- Identification of data sources;
- Selection of the time(s) and the period over which data was to be collected.
-

5.2.1 Selected intersections

The intersection bounds were chosen to be sufficiently far away from other signalised intersections in order to avoid the influence of platooning waves and to be well represented by the simulation model that did not take the platooning influence into consideration. Also

the data was collected at intersection legs in which one exclusive single RTL exists to satisfy the assumptions of the simulation model.

The three intersections chosen were Hodges Drive/Joondalup Drive, Marmion Avenue/Hepburn Avenue, and Marmion Avenue/Whitfords Avenue. Brief descriptions of the selected intersections are given below:

Hodges Drive and Joondalup Drive Intersection

Joondalup Drive is a major road that connects the northern suburbs of Perth, Western Australia, starting at T-section with Ocean Reef Road. Hodges Drive is a main west-east road in Joondalup, north of Perth. Hodges drive begins in the suburb of Ocean Reef and runs through the residential areas in Ocean Reef, Connolly and Heathridge, before intersecting with Joondalup Drive and continuing from there as Grand Boulevard. This intersection is located in very close proximity to Edith Cowan University (ECU) and Lakeside Shopping Centre.

Data was collected at the west side of the intersection which consists of two through lanes, a single exclusive right turn lane and a left turn slip lane as indicated in the map in Figure 5.1.

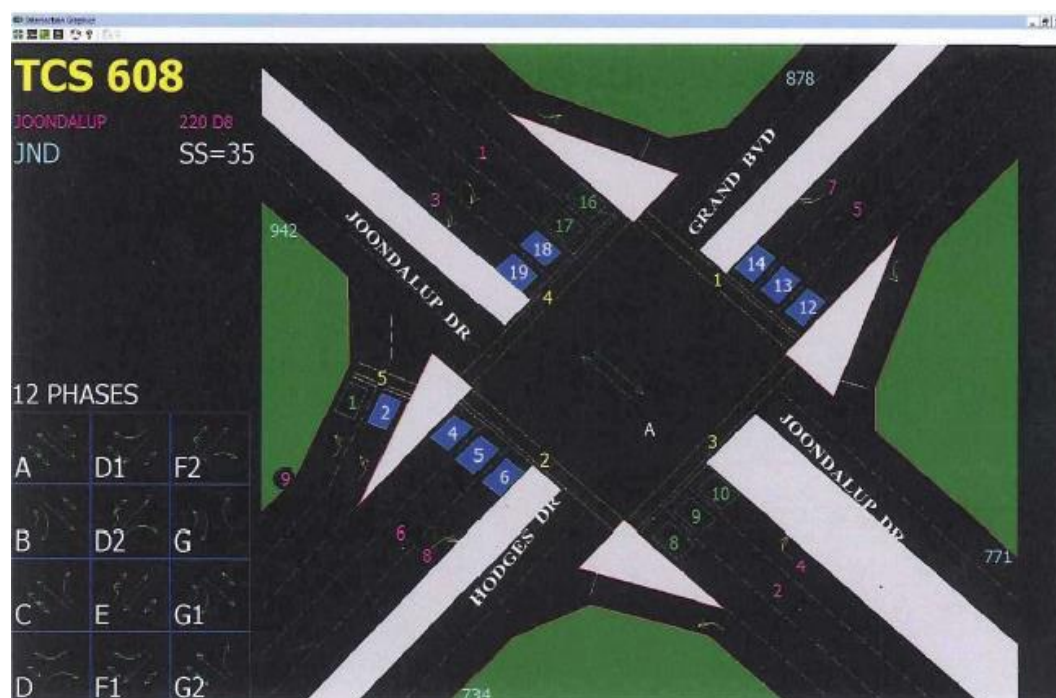


Figure 5.1 Map of study intersection Hodges Drive and Joondalup Drive.

Marmion Avenue and Hepburn Avenue Intersection

Marmion Avenue is an arterial road in the northern coastal suburbs of Perth, Western Australia, connecting the suburb of Trigg at its southerly end with Yanchep at its northerly end. In general it runs parallel to the Indian Ocean coastline, as well as the Mitchell Freeway and Wanneroo Road to the east. Hepburn Avenue is an arterial east-west road in the northern suburbs of Perth, Western Australia. The road links Sorrento in the west with Malaga and Whiteman in the east, as well as major road routes into central Perth.

Data was collected at the east side of the intersection which consists of two through lanes, a single exclusive right-turn lane as well as a left turn lane as indicated in the map in Figure 5.2.

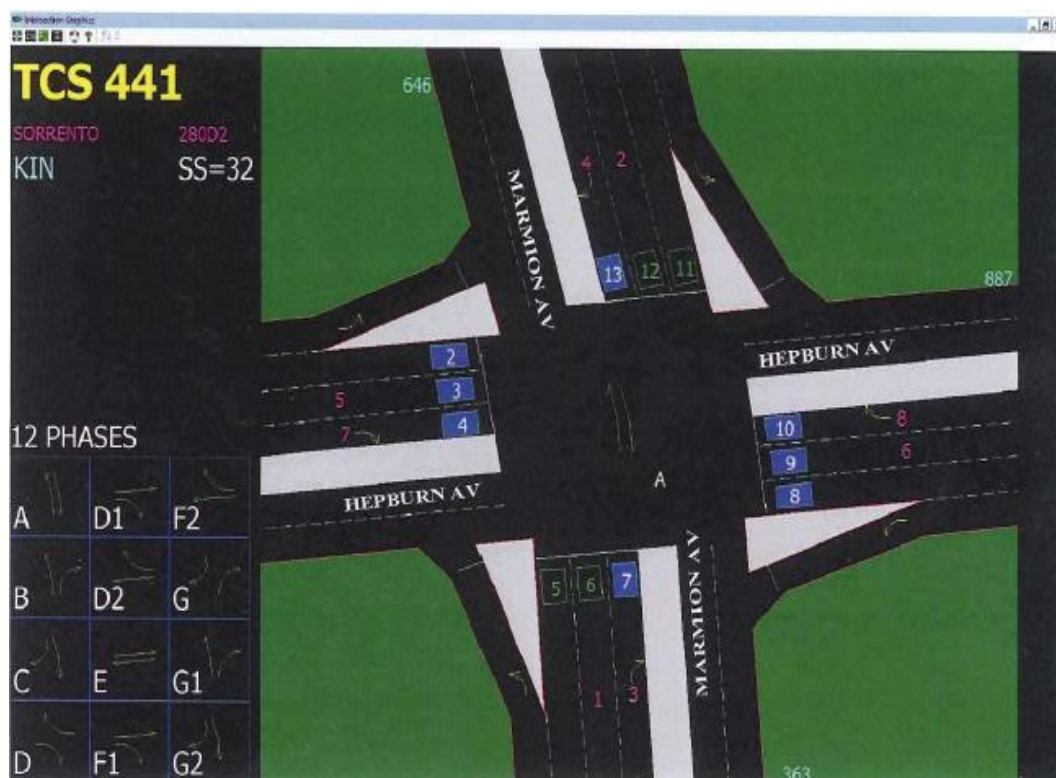


Figure 5.2 Map of study intersection Hepburn Avenue and Marmion Avenue.

Marmion Avenue and Whitford Avenue Intersection

Whitfords Avenue is an arterial east-west road located in the northern suburbs of Perth, Western Australia. It connects the western suburbs of Hillary's, Mullaloo and North Shore to eastern suburbs such as Kingsley. Marmion Avenue, as mentioned above, is an arterial road that runs north-south. The significance of this intersection is due to the existence of Whitford

Shopping Centre (located at the south-west corner of the intersection), and also its close proximity to the Mitchell Freeway.

One of the problems with this particular intersection is the existence of an underground tunnel below the south bound lanes to the north of the intersection that prevents the extension of the right turn lane at this location to accommodate the increasing traffic at this point.

Data was collected at the south side of the intersection. Similarly to the above mentioned intersections, this part of the intersection consists of two through lanes, a single exclusive RTL and a left turn lane as illustrated in Figure 5.3.

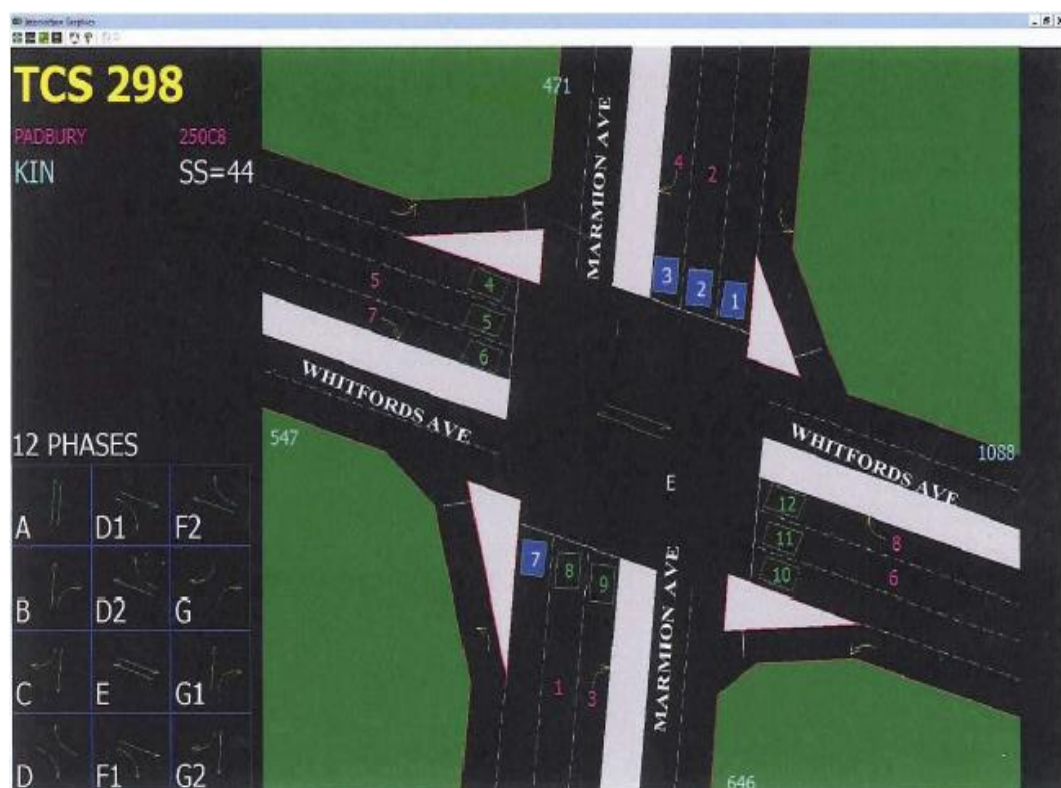


Figure 5.3 Map of study intersection Whitford Avenue and Marmion Avenue.

5.2.2 Model inputs and outputs parameters

The data required from each intersection to validate the model can be classified into two parts:

- 1) Input parameters to the simulation model:
 - The time gap between consecutive vehicles (λ),
 - The signal phase type and timing,
 - The turning probability value,

-
- The existing length of the subject RTL.

2) Output parameters to validate the simulation model:

- The 95th percentile of the maximum queue length,
- The percentage of overflow cycles,
- The percentage of blockage cycles.

5.2.3 Data sources

There were two sources of the data used for validating the simulation model.

1) Main Roads Western Australia (MRWA)

The following information was obtained from MRWA:

- Peak-hour traffic volume of the approach traffic.

This information was required to calculate the time gap between two consecutive vehicles (λ). The Main Roads Traffic Engineering Standards (TES) team provided the peak-traffic volume for each lane at the aforementioned intersections through Sydney Coordinated Adaptive Traffic System (SCATS) reports. TES advised that it was best to collect traffic data on Tuesdays, Wednesdays or Thursdays for the consistency of the traffic behaviour across those days.

- Signal phase types and timings were provided by the Traffic Operation Centre at MRWA through comprehensive reports (see Appendix C).
- The existing right turn lane lengths were provided by Road Network Services at MRWA along with aerial images (see Figures 5.4a-5.4c).
- The right turn probability was determined by the SCATS reports in which the traffic volume for each lane was specified.

2) Field observation

The following information was observed at the intersection sites:

- The maximum queue length for each cycle (just prior to a green light) to calculate the 95th percentile over the peak-hour,

-
- The total number of signal cycles,
 - The number of cycles in which a blockage presented,
 - The number of cycles in which an overflow presented.

In the simulation model a distinction is made between the total number of overflow cycles and the number of overflow cycles which actually result in through traffic being delayed. Similarly a distinction is made between the total number of blockage cycles which actually result in turning vehicles being delayed.

In the field it was only possible to observe the total number of overflow cycles and the total number of blockage cycles. Specifically, it was not possible to identify the number of overflow cycles that caused delay to through lane traffic because of the availability of the second through lane. Also it was not possible to determine which blockage cycles caused the turning traffic to be held up due to the lack of vision to determine whether turning vehicles had been held up while the green arrow was on.

5.3 Data Collection and Calculation Methods

Data collection took place during the traffic peak-hour identified from the SCATS reports. Teams of two persons were organised to record the queue lengths (number of vehicles) in the RTL and in the adjacent through lane at the end of each red signal, count the total number of cycles, and count the number of cycles in which a blockage or overflow were observed. Each team was provided with a copy of the recording sheet form included in Appendix D.

Due to the lack of monitoring cameras, it was awkward to count the RTL maximum queue by observation, as once the RTL overflowed it was hard to determine which cars intended to turn. For this reason the validation was limited to the through lane queue.

5.3.1 Collection of field data

Field data was observed and recorded as outlined below:

- The total number of cars in the through lane queue was recorded at the end of the through lane red phase, monitoring the last vehicle in the queue. When the through signal turned green, the number of right turning cars, before the monitored car reached the RTL taper, was recorded and then subtracted from the total number of cars in the through lane to calculate the maximum numbers of the cars that go straight.

(the maximum queue length in the through lane). This was done for all the cycles within the peak hour, and the 95th percentile queue was calculated and recorded (Table 5.3).

- The total number of cycles: was calculated during peak-hour. A cycle was counted every time the through lane light turned red.
- The total number of blockage cycles: was observed as the number of cycles in which the queue in the through lane exceed the RTL length (i.e. blocking any further cars from entering the RTL).
- The total number of overflow cycles: was observed as the number of cycles in which the number of cars in the RTL exceeded the RTL length, resulting in turning cars queuing in the through lane
- The overflow and the blockage percentages were calculated and recorded in Table 5.3.

5.3.2 Calculation of inputs for the simulation model

The processes used to estimate the simulation model inputs are outlined below:

- The time between two consecutive cars (λ)

Traffic volume at the peak hour of the subject bound of the intersections was obtained from SCATS reports provided by MRWA. A sample copy of such a report is attached in Appendix E. It is important to note that the SCATS reports record the traffic volume at each detector, thus to input the information into the simulation model, the approach traffic volume was calculated as the sum of the volumes detected by both the RTL detector and the adjacent through lane detector. The time between consecutive cars (λ) was calculated using Equation 5.1

$$\lambda = 3600 / (v_r + v_s) \tag{5.1}$$

where

v_r is the peak hour traffic volume of the RTL (number of cars),

v_s is the peak hour traffic volume of the through lane (number of cars).

- Signal phase types and timings

The idea was to obtain the signal phase types and timings (for peak-hour) from the traffic operation centre reports provided by MRWA and represent this information as a configuration matrix (see Section 4.3) which is needed as an input for the simulation model. The traffic operation centre reports show slightly different timings for each cycle as the system is actuated based on traffic movements and volumes. Therefore an average timing for each phase during the peak hour was used as the phase period. For each phase, the phase type was specified from the SCATS reports' attached maps illustrated in Figures 5.1 - 5.3.

- The RTL existing length

Aerial images were sent by Road Network Services MRWA indicating the length of the RTL at the subject leg (Figure 5.4-5.6). These lengths were converted to equivalent passenger cars using the average length required to store a passenger car of 7 m that was substantiated by Kikuchi et al. (1993) using field data observations. The majority of traffic consisted of normal passenger cars, however, when other vehicles were presented the equivalency factors in Table 5.1 (AASHTO, 1990) were used to convert them to their equivalent passenger car length.

Table 5.1 Vehicle length equivalency factors (adapted from AASHTO 1990).

Vehicle Type	Equivalency Factor
Passenger car	1
Bus	2.1
Truck	2.9
Recreational Vehicle	2.2

- Turning probability

The turning probability was calculated using the following Equation:

$$Right_Turn_Probability = \frac{v_r}{v_r + v_s} . \quad (5.2)$$

The above inputs were calculated for each of the three intersections being considered and are summarised in Table 5.2.

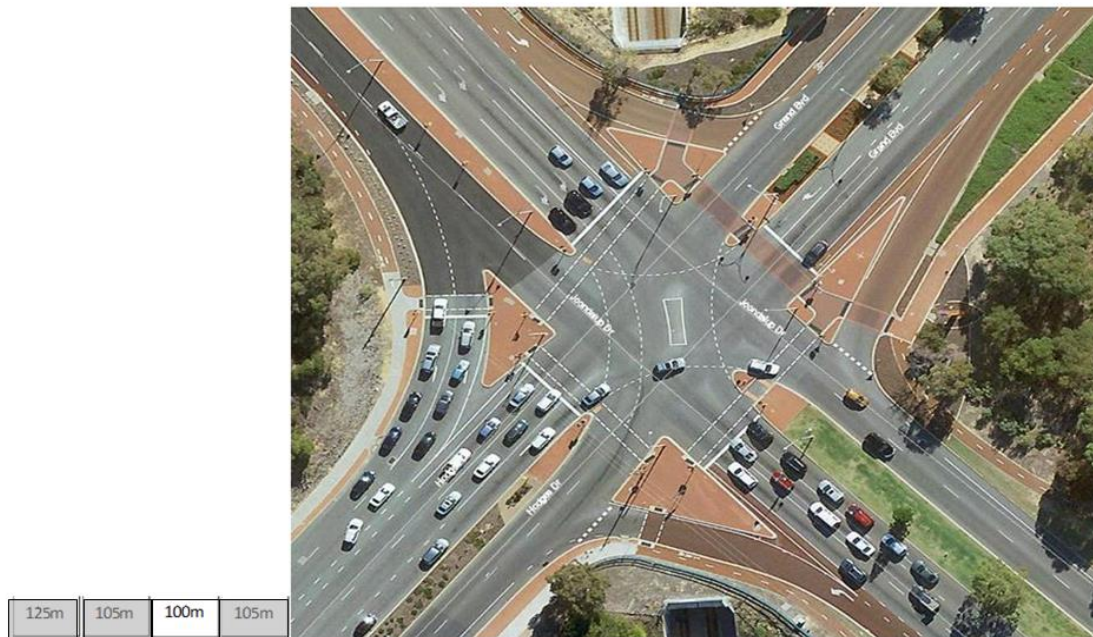


Figure 5.4 Aerial image indicating the approximate length of the RTL at Hodges Drive and Joondalup Drive intersection. each location.



Figure 5.5 Aerial image indicating the approximate length of the RTL at Marmion Avenue and Hepburn Avenue intersection.



Figure 5.6 Aerial image indicating the approximate length of the RTL at Marmion Avenue and Whitford Avenue intersection.

*The unshaded length indicates the subject RTL length in this study.

Table 5.2 Intersection information and inputs data for the simulation model

Intersection Name	Type of RTL	Signal Type	Current RTL Length (veh.)	Peak-Hour	Peak-Hour Traffic Volume			Model Signal Phase Type and Timing Matrix (Configuration matrix)				$\lambda_{approaching}$
					Thr.L Volume (vphpl.)	RTL Volume (vphpl.)	Turning probability					
Joondalup Dr. and Hodges Dr. ID 608	This intesection has the same peak hour for both RTL and Thr.L											
	Exclusive -Single	Protected	14	8:00-9:00 (Detector 5-6)	(Detector 5) 320	(Detector 6) 396	55%	0	0	1		5
								0	1	0		
								68	47	26		
Marmion Ave. And Hepburn Ave. ID 441	This intesection has different peak hours for RTL and Thr.L											
	Exclusive -Single	Protected	10	17:00-18:00 (Detector 9)	(Detector 9) 327	(Detector 10) 254	44%	0	0	1		6.1
								0	1	0		
				15:30-16:30 (Detector 10)	(Detector 9) 249	(Detector 10) 295	54%	102	36	35		6.6
								0	0	1		
									0	1	0	
105									36	34		
Whitford Ave. And Marmion Ave. ID 298	This intesection has different peak hours for RTL and Thr.L											
	Exclusive -Single	Protected	8	6:15-7:15 (Detector 2)	(Detector 2) 932	(Detector 3) 67	7%	1	1	0	0	3.6
								0	1	0	1	
				8:00-9:00 (Detector 3)	(Detector 2) 487	(Detector 3) 301	38%	66	16	50	21	4.5
								1	1	0	0	
									0	1	0	1
53									24	60	23	

The simulation model was run using the inputs specified in Table 5.2 and the simulation outputs recorded in Table 5.3.

Table 5.3 Simulation and observation results for the study intersections

Intersections Name and ID	Blockage Percentage		Overflow Percentage		95 th Percentile Queue Length (veh.)	
	Observation	Sim. Model	Observation	Sim. Model	Observation	Sim. Model
Joondalup Dr/Hodges Dr. ID 608 (peak hour 8:00-9:00)	11%	16%	23%	19%	26	31
Marmion Av/Hepburn Av. ID 441 (peak hour 17:00-18:00)	70%	81%	20%	11%	30	40
Marmion Av/ Hepburn Av. ID 441 (peak hour 15:30-16:30)	40%	54%	28%	36%	32	35
Whitford Av/Marmion Av. ID 298 (peak hour 6:15-7:15)	100%	100%	0%	0%	40	37
Whitford Av/Marmion Av. ID 298 (peak hour 8:00-9:00)	90%	92%	5%	6%	37	34
Accuracy Level	80%		78%		84%	

5.4 Results and Discussion

At Intersection ID 608 (Joondalup Dr and Hodges Dr) the peak hour for the RTL was the same as the peak hour of the through lane at the subject bound of the intersection, so the inputs for this intersection were calculated once (i.e. only for a single peak hour). However at Intersection 298 (Whitford Av and Marmion Av) and Intersection 441 (Hepburn Av and Marmion Av), the traffic peak hour for the RTL was different to that of the through lane so there were two sets of inputs specified for each of those intersections (i.e. one set for each peak hour).

Accuracy levels were calculated using Equation 5.3 adapted from Qi et al. (2012).

$$Accuracy\ Level = 1 - Avg \left[\frac{|R_{Sim} - R_{Obs}|}{R_{Obs}} \times 100\% \right] \quad (5.3)$$

where R_{Sim} denotes the simulation value for the quantity under consideration, and R_{Obs} denotes the observed field value of the quantity under consideration.

Accuracy levels were calculated for the percentage of blockage cycles, the percentage of overflow cycles, and the maximum through lane queue length and the results recorded in Table 5.3.

The simulation model reports on many parameters such as mean wait time, 95th percentile of the RTL and the through lane maximum queues, the total overflow percentage, the percentage of the overflow cycles that cause problems, the total blockage percentage, and the percentage of blockage cycles that cause problems, however, the validation was limited to three parameters namely :1) The 95th percentile of the through lane maximum queue, 2) The overflow percentage; and 3) The blockage percentage.

The simulation model yielded results that were consistent with field observations. The accuracy level of the simulation model was 78% for the percentage of cycles in which an overflow occurred, while the accuracy level for the percentage of cycles in which a blockage occurred was 80%. The comparison also showed a high accuracy level of 84% when comparing the 95th percentile maximum of the through lane queue with that estimated by the simulation model.

5.5 Conclusions

Data gathered through field observation at three urban WA intersections and from MRWA data bases were used to estimate the key parameters required by the simulation model presented in Chapter 4.

Due to the existence of a second through lane, the overflow situation could not be assessed accurately. Also the lack of vision made it difficult to judge the blockage cycle in which an actual delay happened. The maximum RTL queue could not be determined as it was hard to spot which the number of cars tending to turn right once the RTL overflowed.

For those reasons the validation was limited to The total number of overflow cycle percentage, the total number of the blockage cycle and the 95th percentile of the through lane maximum queue.

The outputs of the simulation model that could be readily observed in the field were compared to data recorded via on-site observation of the three intersections. These outputs were the 95th percentile through Lane queue length, the percentage of blockage cycles, and the percentage of overflow cycles.

The simulation outputs showed strong agreement with what was observed on site, with accuracy level ranging from 78% to 84% over the three outputs across the three intersections.

CHAPTER 6

OPTIMISATION ANALYSIS OF INTERSECTIONS WITH SPLIT PHASE

6.1 General

It is unrealistic to expect approaching traffic volumes at urban intersections to be equal to the traffic volumes for the opposite directions. Moreover, it is common that the demographic characteristics and the direction of the Central Business District (CBD) affect the relative balance of those traffic volumes throughout the day, for example, in some intersections the peak-hour occurs for north-bound traffic in the morning while, in the afternoon it occurs at the opposite direction i.e., south-bound. This situation creates a significant traffic volume differential between approaching and its opposing traffic.

It is logical to allocate more green time to the traffic volume which is reaching its peak, thus compromising the green time allocated for the opposing traffic. This will only apply for the split phase as the movement for both right-turn traffic and through traffic happens concurrently following by the movement in the opposite approach of the intersection (Figure 4.4a). To optimise such intersections, the effectiveness of change or alternate green times should be investigated.

6.2 Methodology

Generally simulation is a reliable method for evaluating or optimising a complex system in which random variables are involved, such as traffic flow at signalised intersections (see section 1.4). Hence, the developed simulation model (Chapter 4) was used to simulate the situation when there is a large difference between the approaching and opposing traffic volumes. It seems logical to allocate more green time (GT) to the bound with more traffic volume, thus compromising the allocated (GT) for opposing traffic. In order to examine the impact of this solution we need to identify a suitable metric for verification. These metrics could be limited to mean wait-time (MWT), and the standard deviation of wait time Std.WT.

The latter should help ensure that applying less (GT) for the direction with less traffic volume does not compromise the functionality of one direction at the cost of the other.

It is logically to assume that the GT of the split phase should be distributed equally between equally distributed approaching traffic volume and the opposing traffic volumes. By using this case we can compare and evaluate the two possible metrics MWT and Std.WT at the expected optimal timing, which is 30/30 sec in the case of a 120 sec cycle, to decide which metric should be used to optimise other combinations of traffic volumes.

The idea is to simulate this situation, using the developed simulation model (Chapter 4) when the approaching and the opposite traffic are equal, and then analyse the trend of the overall MWT and the overall Std.WT at the subject legs of the intersection to provide a clear idea of which metric is more consistent. Then by using this metric, an optimal timing is calculated for other traffic volume combinations. In this study the larger traffic volume has been referred to as the approaching traffic volume.

6.2.1 Determine a reliable metric to measure the optimal timing

The simulation model was used to simulate a 120 sec cycle of split phase for a typical signalised intersection (Figure 1.1) for traffic volumes of 200, 300, 400, 500, 600, 700 800 and 900 vphpl; each run was done with 30%, 50%, 70% turning probability and an incremental time of 2 sec. Then the overall MWT and Std.WT for equal approaching and opposite traffic were calculated.

Once the metric was identified the program was run to calculate the optimal GT values for all combinations of the abovementioned traffic volumes with a 2 sec increment for the approaching traffic GT while, reducing the (GT) allocated for the opposing traffic by 2 sec for each increment.

6.3 Results and Discussion

A detailed description of the simulation's findings and their implications are discussed in the following subsection:

6.3.1 Identifying the appropriate metric

At 30/30 sec GT, the overall MWT , for equal approaching and opposite traffic volume was consistently the minimum for all the trials, examples of which are illustrated in Figures 6.1 - 6.8; however, the overall Std.WT was not consistent yet the variation was minor (fraction of

second). This identified the minimum overall MWT value as the reliable metric for verifying the optimal signal timings allocated for a particular combination of approaching and opposing traffic volumes. Hence, the GT corresponding to the minimum overall MWT should be the optimal GT recommended in the case of different approaching and opposing traffic volumes. Notably, parameters other than traffic volumes, such as the RTL length, were fixed for all trials.

6.3.2 Calculating the optimal timing for traffic volume combinations

After establishing that the MWT is a reliable metric, the program was run to calculate the optimal GT values for all above combinations of traffic volumes, with GT incremental for the approaching traffic volumes of 2 sec while, reducing the GT allocated for the opposing traffic volumes by 2 sec. The trials were done for turning probability values of 30%, 50%, 70% for each increment of the approaching traffic GT. The optimal time, along with the MWT for each combination, was extracted from the simulation results (Table 6.1-6.3).

Table 6.1 Split phase optimal green time (s) for 30% turning probability

		Peak Direction (vphpl)							
		200	300	400	500	600	700	800	900
Opposing Direction (vphpl)	200	30 (34.87)	48 (33.70)	50 (32.05)	52 (30.61)	52 (29.86)	52 (29.23)	52 (28.82)	52 (28.61)
	300		30 (35.55)	42 (35.04)	48 (34.01)	48 (33.14)	48 (32.53)	50 (31.95)	50 (31.72)
	400			30 (36.13)	42 (35.97)	44 (35.38)	46 (34.90)	46 (34.50)	46 (34.22)
	500				30 (36.78)	38 (36.77)	42 (36.51)	44 (36.29)	44 (36.14)
	600					30 (37.45)	38 (37.56)	36 (37.60)	40 (37.47)
	700						30 (38.21)	34 (38.49)	36 (38.58)
	800							30 (38.98)	34 (39.35)
	900								30 (39.91)

*The minimum wait-time values (s) are shown in brackets

Table 6.2 Split phase optimal green time (s) for 50% turning probability

		Peak Direction (vphpl)							
		200	300	400	500	600	700	800	900
Opposing Direction (vphpl)	200	30 (34.70)	48 (33.50)	52(31.68)	52(30.18)	54(29.17)	54 (28.36)	54(27.76)	54(27.40)
	300		30 (35.29)	42(34.74)	50(33.48)	50 (32.49)	52 (31.72)	52 (31.11)	52 (30.55)
	400			30 (35.77)	42 (35.55)	46 (34.84)	48 (34.08)	48 (33.56)	48 (33.10)
	500				30 (36.30)	38 (36.23)	44(35.08)	44 (35.29)	46 (35.00)
	600					30 (36.85)	38 (36.84)	42 (36.67)	44 (36.34)
	700						30 (37.47)	38 (37.58)	40 (37.40)
	800							30 (38.04)	38 (38.23)
	900								30 (38.67)

*The minimum wait-time values (s) are shown in brackets

Table 6.3 Split phase optimal green time (s) for 70% turning probability

		Peak Direction (vphpl)							
		200	300	400	500	600	700	800	900
Opposing Direction (vphpl)	200	30 (34.82)	48 (33.67)	50 (31.92)	52 (30.71)	52 (29.74)	52 (19.18)	52 (28.78)	52 (28.55)
	300		30 (35.41)	44 (35.00)	46 (34.04)	48 (33.11)	48 (32.5)	50 (32.03)	50 (31.68)
	400			30 (36.14)	42 (35.97)	44 (35.42)	46 (34.91)	46 (34.50)	46 (34.20)
	500				30 (36.75)	36 (36.82)	42 (36.53)	44 (36.28)	44 (36.15)
	600					30 (37.52)	38 (37.61)	38 (37.60)	40 (37.55)
	700						30 (38.21)	34 (38.45)	36 (38.57)
	800							30 (38.93)	32 (39.31)
	900								30 (39.83)

*The minimum wait time-values (s) are shown in brackets

6.3.3 The impact of applying the optimal timing on MWT reduction

To illustrate the significance of applying the previous recommended optimal timing (Table 6.1-6.3) on MWT, a case study of 30% turning probability was investigated. The MWT was calculated for several combinations of approaching traffic volumes of 900, 800, 700, 600 and 500 vphpl and opposing traffic volumes of 200, 300, 400, 500, 600 and 700 vphpl.

The MWT was calculated when applying 30/30 s for both directions, regardless of the difference between the approaching and opposing traffic volumes. Then this MWT was compared against the MWT calculated when applying the recommended optimal timing; the resultant MWT reduction percentage was calculated (Table 6.4).

Table 6.4 Percentage of reduction in wait-time by applying the optimal split phase timings recommended in Table 6.1

App. Traffic volume (vphpl)	900			800			700			600			500		
Opposing Traffic Volume (vphpl)	Wait-Time Applying 30/30	Wait-Time Applying Optimal Timing	Wait-Time Reduction %	Wait-Time Applying 30/30	Wait-Time Applying Optimal Timing	Wait-Time Reduction %	Wait-Time Applying 30/30	Wait-Time Applying Optimal Timing	Wait-Time Reduction %	Wait-Time Applying 30/30	Wait-Time Applying Optimal Timing	Wait-Time Reduction %	Wait-Time Applying 30/30	Wait-Time Applying Optimal Timing	Wait-Time Reduction %
200	39.7	28.6	28	39.7	29.8	25	37.4	29.2	22	36.9	29.9	19	36.4	30.6	16
300	39.1	31.7	19	37.1	31.9	16	37.3	32.5	13	36.8	33.1	10	36.6	34.0	7
400	39.8	34.2	14	38.8	34.5	11	37.5	34.9	7	36.9	35.4	4	36.4	36.0	1
500	40.1	36.1	10	38.6	36.3	6	37.6	36.5	3	37.2	36.8	0	36.8	36.8	0
600	40.3	37.5	7	38.4	37.6	2	38.0	37.6	1	37.5	37.5				
700	39.8	38.6	3	38.9	38.5	1	38.2	38.2	0						

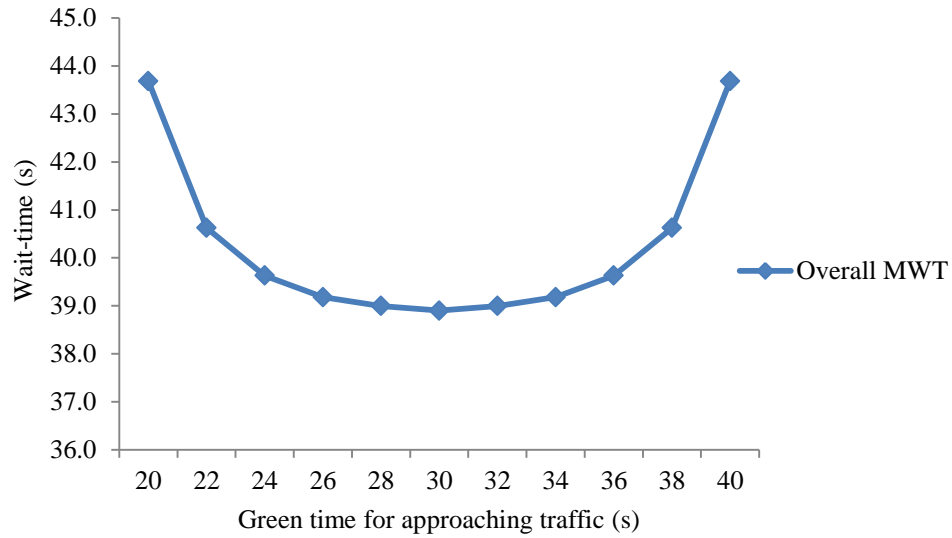


Figure 6.1 Overall mean wait-time for equal approaching and opposing traffic volumes of 800 vphpl and turning probability of 30%

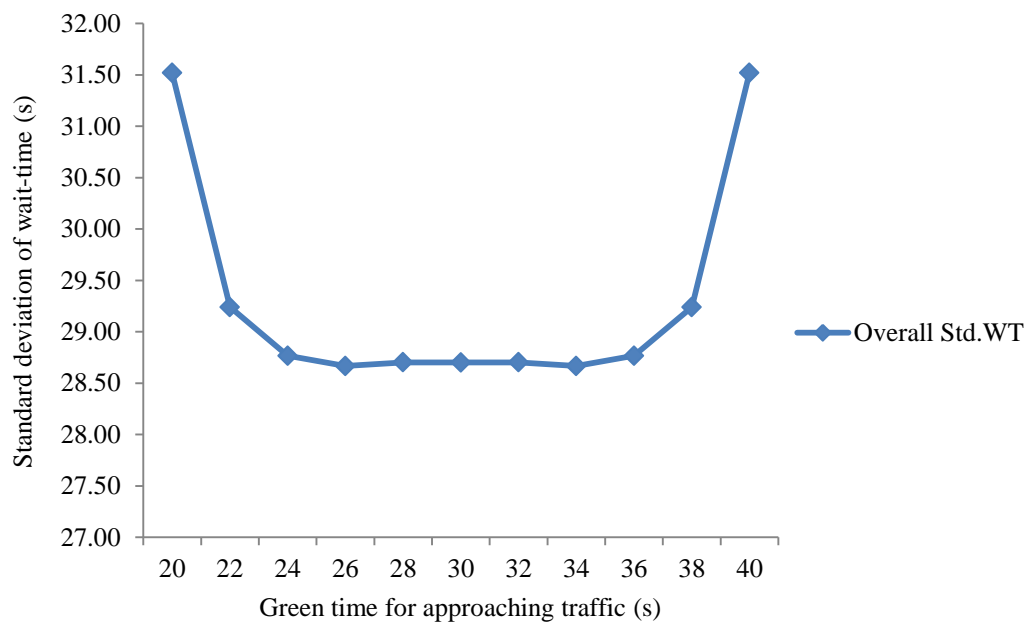


Figure 6.2 Overall standard deviation of wait-time for equal approaching and opposing traffic volumes of 800 vphpl and turning probability of 30%

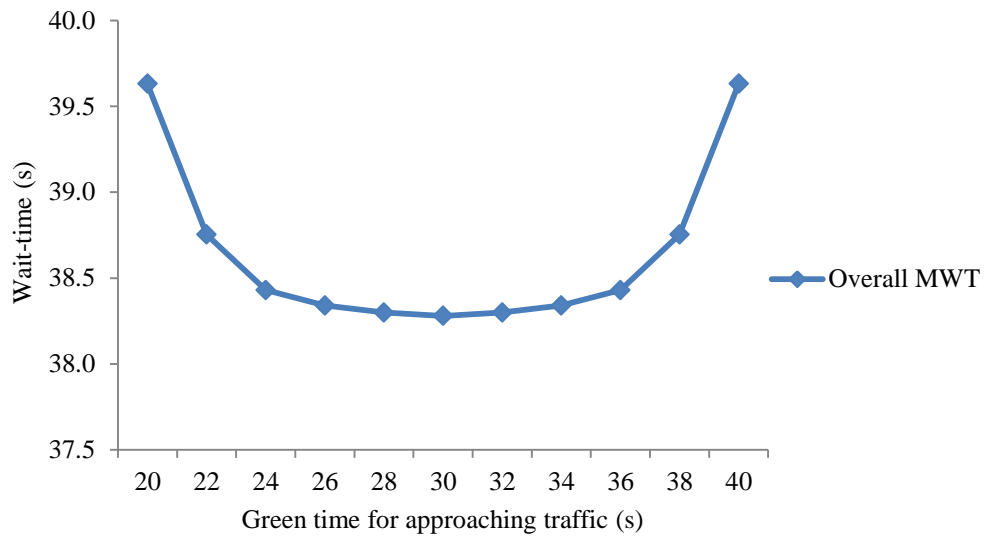


Figure 6.3 Overall mean wait-time for equal approaching and opposing traffic volumes of 700 vphpl and turning probability of 30%

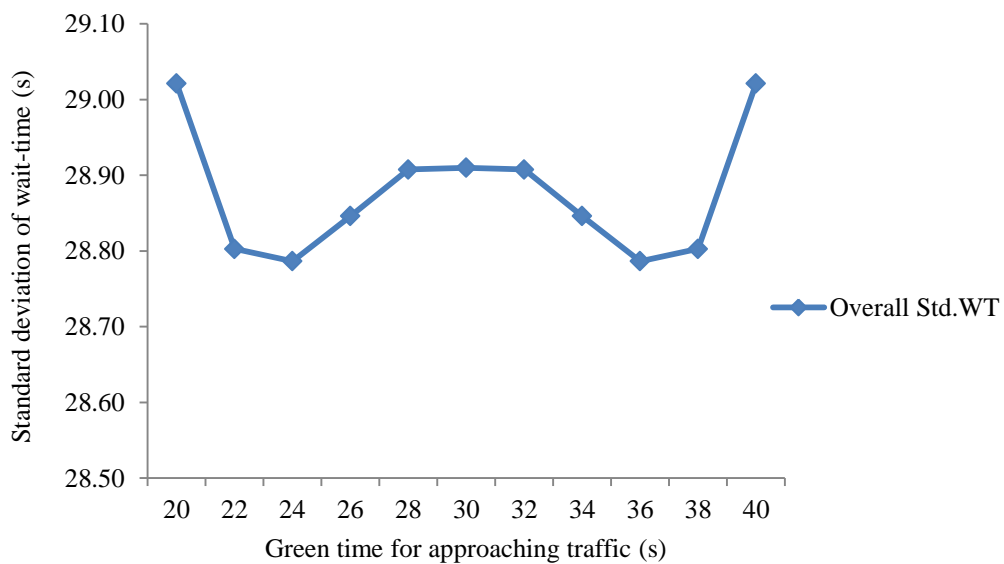


Figure 6.4 Overall standard deviation of wait-time for equal approaching and opposing traffic volumes of 700 vphpl and turning probability of 30%

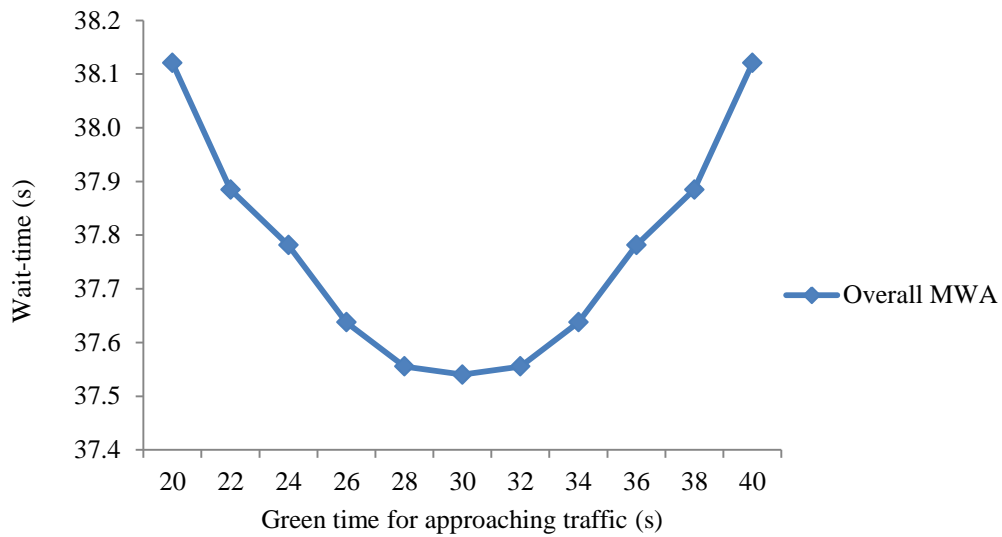


Figure 6.5 Overall mean wait-time for equal approaching and opposing traffic volumes of 600 vphpl and turning probability of 70%

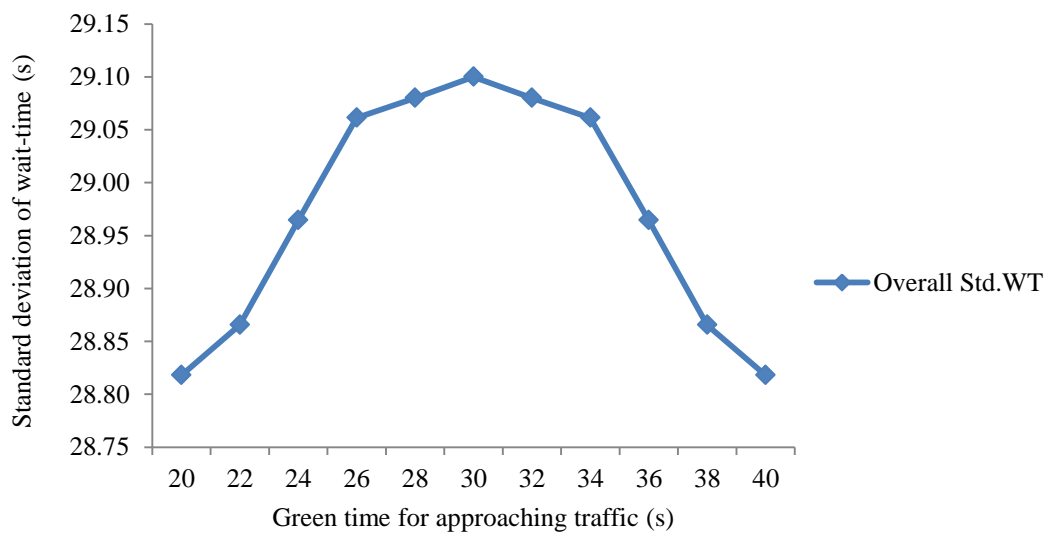


Figure 6.6 Overall standard deviation of wait-time for equal approaching and opposing traffic volumes of 600 vphpl and turning probability of 70%

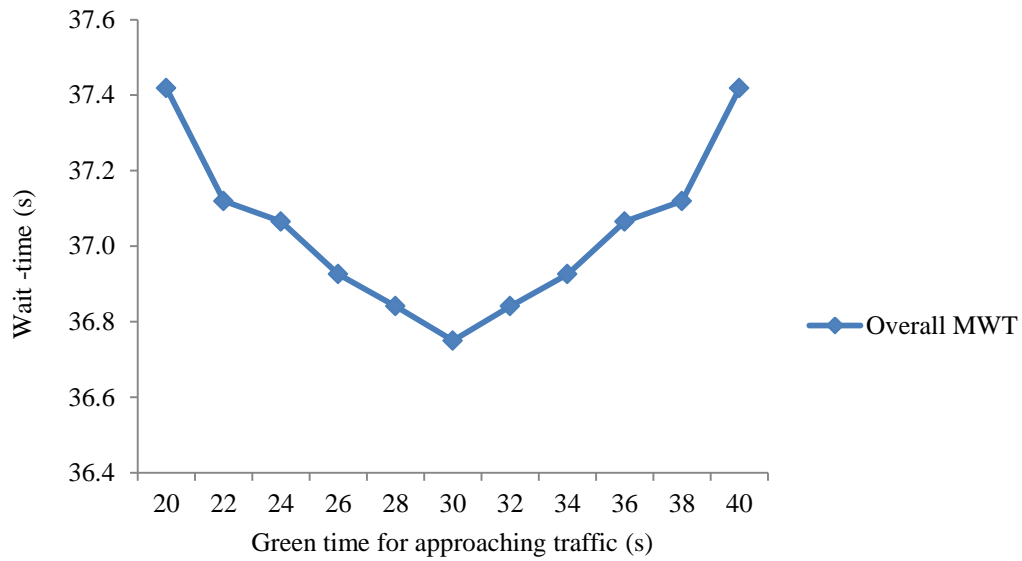


Figure 6.7 Overall mean wait-time for equal approaching and opposing traffic volumes of 600 vphpl and turning probability of 50%

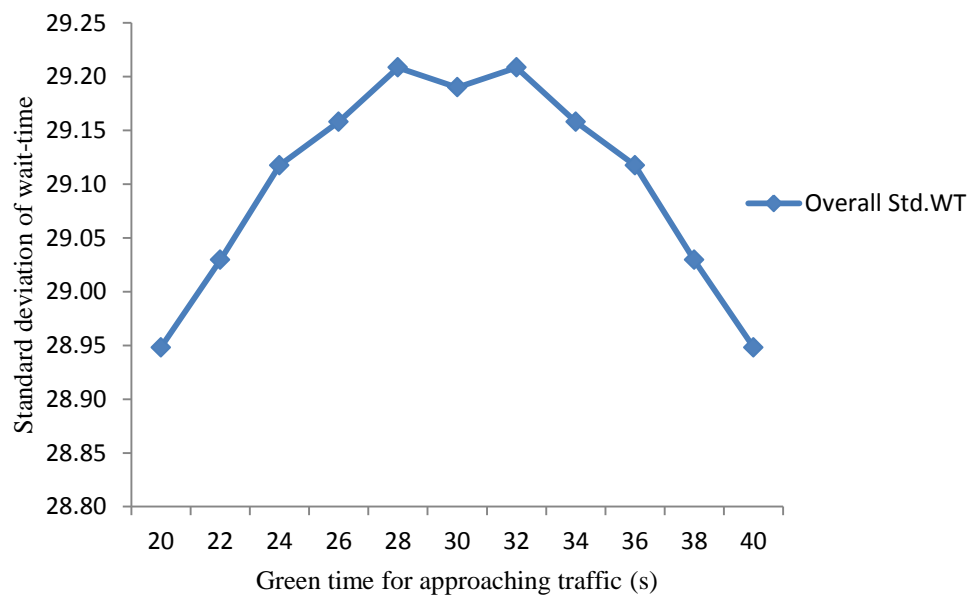


Figure 6.8 Overall standard deviation of wait-time for equal approaching and opposing traffic volumes of 600 vphpl and turning probability of 50%

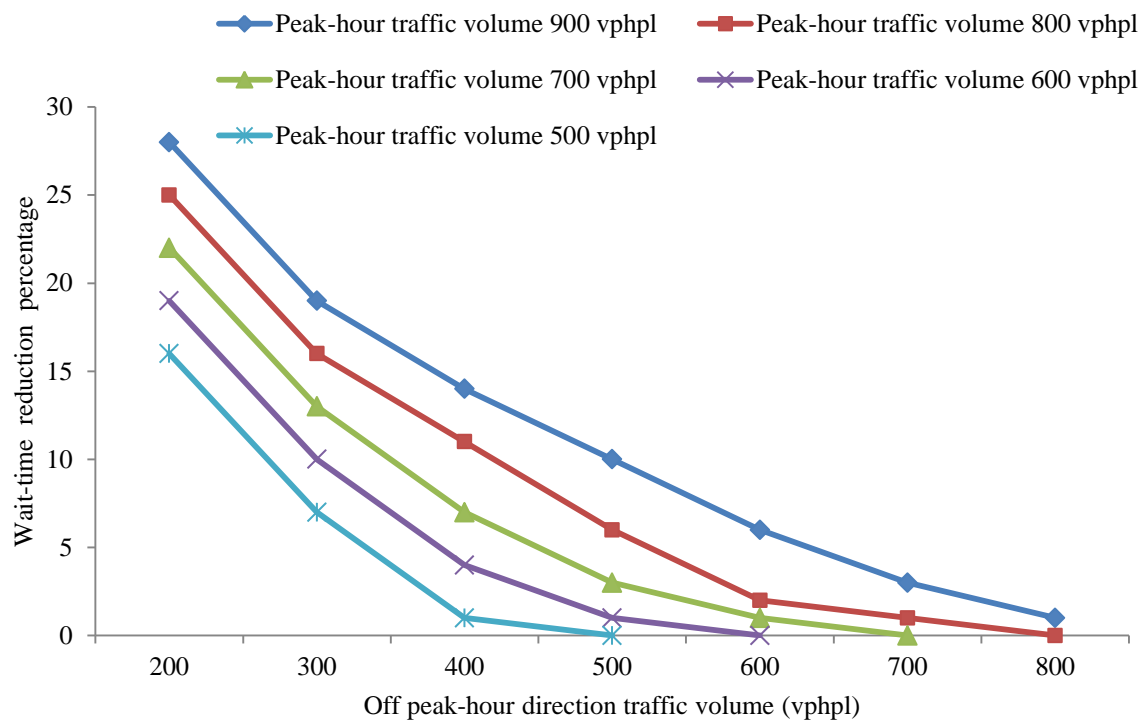


Figure 6.9 Percentage of wait-time reduction using the optimal time versus the fixed 30/30 green time in 120 sec cycle. (Case study: turning probability 30%)

6.4 Conclusions

Applying the recommended optimal timing reduces the MWT by up to 28%; however, when the difference is less than 100 vphpl the MWT reduction is less than 5% (Table 6.4)

By using the optimal time, the reduction was found to be significant when there is a large difference between the approaching traffic and the opposing traffic volumes. However, when the difference is less than 100 vphpl the MWT reduction is minor.

Hence synthesising the split phase timing to offer more GT, at the bound subject to the peak- hour or the larger traffic volume by compromising the GT for the opposite direction, could reduce the overall MWT at signalised intersection. This MWT saving increases progressively when the difference in traffic volume at two opposite bounds increases (Figure 6.9).

This adjustment can be applied for intersections that present a substantial difference between two opposite traffic volumes or when the peak-hour alternates between the two directions throughout the day based on the traffic movements associated with business hours.

CHAPTER 7

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

7.1 Summary

Right-turn lane (RTL) design is a major consideration when it comes to the overall design of a signalised intersection due to the random nature of the determining factors such as arrival rate, departure rate and headway and the constraints imposed by the opposing and crossing traffic. Some intersections have physical restrictions which impose additional design limitations.

The RTL length should ideally be sufficient to provide storage for turning cars waiting for the green light or an appropriate gap in the opposing traffic (in the case of permissive phase), and in addition provide sufficient distance for decelerating comfortably without the need to reduce speed in the through lane to minimise the interruption of the through traffic. When estimating the deceleration length in general, engineers have been faced with two questions:

1. What is the appropriate value of the comfortable deceleration rate?
2. Would a constant comfortable deceleration rate be applicable for all the design speeds?

This study examined two analytical models for calculating the deceleration length. The first model is based on a constant deceleration rate (CDR model), while the second takes into account the change in deceleration rate associated with the change of the pavement coefficient of friction (CoF model). The CoF model is defined in terms of the design speed when designing the pavement treatment of the RTL.

The CDR model was used to calculate the RTL length for two values of the deceleration rate; 2.74 m/s^2 and 1.5 m/s^2 and the results compared with the aforementioned guidelines. The deceleration rate value of 2.74 m/s^2 showed similar figures to that of Austroads (2009), TxDOT (2006), and Qi et al. (2012), however, applying the deceleration

rate of 1.5 m/s^2 , the CDR expression resulted in very close figures to that of the AASHTO (2001) recommended values.

Austroroads (2002) and AASHTO (1994) guidelines provided different CoFs determined by the design speed. These coefficients were used by the present study to estimate the RTL deceleration length using the CoF model. The comparison has showed that using the coefficients of friction provided by Austroroads (2002) resulted in an underestimation of the deceleration length comparing with other guidelines. However, applying the coefficients of friction recommended by AASHTO (1994) provided closer figures yet shorter than other guidelines. Using a coefficient of friction of 0.26, which corresponds to deceleration rate value of 2.55 m/s^2 , provided very similar results to the recommended deceleration length by TxDot (2006) and Austroroads (2009) guidelines.

The present study investigated the use of pavement treatment to reduce the required deceleration length when there is a limited space for the RTL. It was found that the required deceleration length decreases significantly when applying high friction treatment for the RTL. The study advocates for the consideration of road pavement management when designing the deceleration length, moreover using the pavement type to increase the coefficient of friction to reduce the deceleration length when necessary.

The design of the RTL storage length should be considered from two equally important viewpoints:

1. Minimising the frequency with which cars overflow the RTL causing the blockage of the through lane;
2. Minimising the frequency with which queues of through traffic block turning cars from entering the RTL.

The current guidelines such as AASHTO (2004) and TxDOT (2006) have limitations in addressing both overflow and blockage situations. Specifically, the guidelines only consider problems associated with overflow. Moreover, there are few previous studies which have considered the integration of the signal phase types in the storage length design.

This study presented a simplified simulation model for estimating the storage length, integrating all phase types and timings. This model was validated using both a recent analytical model and field data. Comparing the recommended RTL lengths with the analytical model yielded very similar results in most signal phase types.

The simulation model showed accuracy levels between 78% and 84% when compared with field data for the percentage of blockage cycles, the percentage of overflow cycles, and the 95th percentile Through Lane queue length.

In addition, the simulation model was utilised for examining the optimal green time allocation in intersections with split phase in which there are different traffic volumes between opposing directions. It was found that by identifying and applying the optimal green time to favour the direction with the large traffic volume, the overall Mean Wait Time can be reduced by up to 28%, when the difference in opposing traffic volumes is 700 vphpl, however, when the difference is less than 100 vphpl the delay reduction is negligible.

7.2 Conclusions

The main conclusions of this study are summarised as follows:

1. Two analytical expressions were analysed to calculate the right turn lane (RTL) deceleration length, one based on a constant deceleration rate (CDR) and another as a function of the coefficient of friction (CoF) which is related to roads pavement design.
2. The deceleration lengths were calculated for two deceleration rate 2.74 m/s^2 and 1.5 m/s^2 using the CDR expression, and compared to American and Australian guidelines and studies namely: Austroads (2009), TxDOT (2006), AASHTO (2001) and Qi et al. (2012). The comparison showed that using a CDR of 1.5 m/s^2 provided similar results to the deceleration length recommended by AASHTO (2001), however when applying the CDR of 2.74 m/s^2 , the results were consistent with the other guidelines.
3. The CoF provided by Austroads (2002) was used to calculate the deceleration length. The comparison showed that the deceleration length estimates were significantly shorter than of those suggested by the aforementioned guidelines. When using the CoF provided by AASHTO (1994), the comparison showed comparable results.
4. An investigation into the impact of the CoF on deceleration lengths showed that changing the treatment of the road pavement can be employed to reduce the deceleration lengths as a result of increasing the friction force between the roads and the vehicles' tyres. It was found that changing the pavement design to increase the CoF from 0.28 to 0.4 decreases the required deceleration length by 30%. This is particularly beneficial for intersections with physical constraints that prevent the extension of the RTL.
5. The study developed a flexible simulation model in which all phase types and timings were integrated in the design of the storage length for all possible approaching traffic volume.

-
6. The simulation model facilitated the consideration of the problem associated with overflow and blockage to estimate the storage length of the RTL that avoids these problems in 95% of cycles.
 7. The simulation model was verified and compared against an analytical model. The comparison exhibited very similar trends and figures.
 8. In addition, the simulation model was validated and compared with field data. The field data validation showed accuracy level ranged between 78% and 84%.
 9. Phase timing was investigated to optimise the green time in split phase in situations where intersections have a large difference between the two opposing traffic volumes. Applying the optimal green time recommended by the investigation resulted in a mean wait time reduction of up to 28%.
 10. The simulation model can be adapted to analyse the situation of existing signalised intersections to find the overflow and blockage percentage and investigate a better phase type and timing to reduce overflow and blockade.
 11. In general, using shorter cycle lengths will result in shorter storage length requirements, however this need to be examined against the mean wait time delay.

7.3 Recommendations for Future Work

- There is need to investigate the appropriate pavement treatment in terms of coefficient of friction and its impact on deceleration rate for different design speeds. It may also be beneficial to incorporate the pavement treatment in the RTL length geometric design to improve safety.
- The proposed model for estimating the storage length deals only with isolated signalised intersections. There is a need to integrate a platoon factor, to cater for the impact of platooned traffic that may be created by other signalised intersections in close proximity.
- There is a need to adjust the simulation model to accommodate two through lanes as most typical intersections hold two through lanes.
- There is a need to investigate the impact of changing the signal types and timing on the mean waiting time to achieve the most efficient solution.
- There is a need to compare the calculated optimised signal timing with other traditional study to ensure the benefit of the used method.

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APPENDIX A:

Pseudo-Code: Initialisation of System and State Parameters

Initialise System Parameters

λ = Average time between arriving vehicles (s);

λ_{oppose} = Average time between arriving vehicles in the opposing through lane (s);

t_{\max} = Simulation duration (s);

p = Probability that an arriving vehicle wants to turn;

t_{gap} = Minimum time gap between opposing vehicles to allow permissive turning (s);
= 4.1 sec. (Kikuchi & Kronprasert, 2010).

T_{\max} = Maximum vehicle capacity of turning lane;

T_{dept} = Departure rate of turning vehicles (vehicles/s);

S_{dept} = Departure rate of through travelling vehicles (vehicles/s);

$Config$ = Matrix defining traffic light sequence and timing. Each column defines a state in the traffic light sequence. The top row indicates the colour of the through light in each state (red=0, green=1), the second row indicates the colour of the turning light in each state (red=0, green=1, permissive=2), and the third row indicates the time(s) of each state;

Initialise State Parameters

$State$ = Starting traffic light configuration (corresponding to columns of $Config$);

S = Number of vehicles in the through lane;

T = Number of vehicles in the turning lane;

M_{track} = Vector indicating which cars in the through lane want to go through (0) and which cars want to turn (1) but cannot get into the turning lane due to a blockage/overflow situation;

Pseudo-Code: Initialise Next event vector (t)

Note: $rand$ denotes a random number chosen from the uniform distribution on the interval $[0,1]$ Update next arrival time by generating a random arrival time using the exponential distribution with mean time between arrival λ ($t(1) = Now + \lambda \ln(1/(1 - rand))$);

If through Light is initially red **Then**

Set next through departure to a large number as no cars can depart through until after the next light change ($t(2) = Large$);

ElseIf through light is initially green **Then**

Set next through departure time to the current time ($t(2) = Now$);

EndIf

If Turning light is initially red **Then**

Set next turning departure to a large number as no cars can depart turning until after the next light change ($t(3) = Large$);

ElseIf Turning light is initially green **Then**

Set next turning departure time to the current time ($t(3) = Now$);

ElseIf Turning light is initially permissive **Then**

Initialise next turning departure time to now ($t(3) = Now$);

Calculate time until next opposing vehicle arrival ($t_{oppose} = \lambda_{oppose} \ln(1/(1 - rand))$);

While $t(3) < Now + \text{Time until turning light changes to red}$

If Time unit next opposing arrival $>$ Minimum time gap to cross **Then**

Next turning departure is can occur before the next opposing vehicle arrives, so update next turning arrival time and exit while loop (

$t(3) = t(3) + 1/T_{dept}$); **Exit While**

ElseIf Next opposing arrival $<$ Minimum time gap to cross **Then**

Increase earliest time for next turning departure by the time until the next opposing arrival ($t(3) = t(3) + t_{oppose}$);

EndIf

EndWhile

EndIf

Update next light change time ($t(4) = Now + Config(3, State)$);

Identify the next event and the time at which it occurs (Next Event = $\arg \min(t)$,

$Now = \min(t)$)

Pseudo-Code: Update system in line with Next event and Update Next Event Vector

Note: $rand$ denotes a random number chosen from the uniform distribution on the interval $[0,1]$, ε denotes a small number, $Large$ denotes a big number.

If Next Event = New Arrival **Then**

If New Arrival = Turning Arrival **Then**

If No Blockage **Then**

 Add a vehicle to tuning lane ($T = T + 1$);

ElseIf Blockage **Then**

 Add a vehicle to the through lane and record that it wants to move to the turning lane

 ($S = S + 1, M_{track}(S) = 1$);

EndIf

ElseIf New Arrival = Through Arrival **Then**

 Add a vehicle to the through lane and record that it wants to go through

 ($S = S + 1, M_{track}(S) = 0$);

EndIf

 Update next arrival time by generating a random arrival time using the exponential distribution with mean time between arrival λ ($t(1) = Now + \lambda \ln(1/(1 - rand))$);

ElseIf Next Event = through Departure **Then**

If There is a vehicle(s) in the through lane **Then**

If The first vehicle in through lane wants to depart through **Then**

 Remove a vehicle from the through lane ($S = S - 1$,

$M_{track} = [M_{track}(2) : M_{track}(S + 1)]$);

 Check if the removal of a vehicle from the through lane frees up a blockage and allows a turning vehicle(s) to move to the turning lane

 ($T = T + 1, S = S - 1, M_{track} = [M_{track}(1 : T_{\max} - 1) \ M_{track}(T_{\max} + 1 : S + 1)]$);

If The turning lane was previously empty **Then**

Set next turning departure time to the current time in order to
force a check if this is feasible at the next iteration ($t(3) = Now$);

EndIf

Update next through departure time by increasing the current departure
time by the average departure rate ($t(2) = Now + 1/S_{dept}$);

ElseIf The first vehicle in through lane want to turn **Then**

Update the next through departure to be considered after the next
turning departure has occurred ($t(2) = t(3) + \varepsilon$);

EndIf

ElseIf There are no vehicles in the through lane **Then**

Update the next through departure to be considered after the next new arrival ($t(2) = t(1) + \varepsilon$);

EndIf

ElseIf Next Event = Turning Departure **Then**

If There is a vehicle(s) in the turning lane **Then**

Remove a vehicle from the turning lane ($T = T - 1$);

If Turning lane had previously been full **Then**

Check if there are vehicles in the through lane that want to turn, and
can now move into the turning lane. If so, move them across ($T = T + 1$,
 $S = S - 1$, $M_{track} = [M_{track}(1:i-1) \quad M_{track}(i+1:S+1)]$, where i is the
position of the first turning car in the through lane queue);

EndIf

If Turning light is currently permissive **Then**

Calculate time until next opposing vehicle arrival

($t_{oppose} = \lambda_{oppose} \ln(1/(1 - rand))$);

While $t(3) < Now + \text{Time until turning light changes to red}$

If Time until next opposing arrival > Minimum time gap to
cross **Then**

Next turning departure can occur before the next
opposing vehicle arrives, so update next turning arrival
time and exit while loop

($t(3) = t(3) + 1/T_{dept}$); **Exit While**

```

ElseIf Next opposing arrival < Minimum time gap to cross
Then
    Increase earliest time for next turning departure by the
    time until the next opposing arrival ( $t(3) = t(3) + t_{oppose}$ );
EndIf
EndWhile
ElseIf Turning light is currently green Then
    Update next turning departure time by increasing the current
    departure time by the average departure rate (
     $t(3) = Now + 1/T_{dept}$  );
EndIf
ElseIf There are no vehicles in the turning lane Then
    Update the next turning departure to be considered after the next new arrival
    or next through departure ( $t(3) = \min(t(1), t(2)) + \varepsilon$ );
EndIf
ElseIf Next Event = Traffic Light Change Then
    Record the change in the traffic light state ( $State = \text{mod}(State - 1, N^{\circ} \text{ of States}) + 1$ );
    If through light changes from red to green Then
        Set next through departure time to the current time ( $t(2) = Now$ );
    ElseIf Through light changes from green to red Then
        Set next through departure to a large number as no cars can depart through
        until after the next light change ( $t(2) = \text{Large}$  );
    EndIf
    If Turning light changes to green from permissive or red Then
        Set next turning departure time to the current time ( $t(3) = Now$ );
    ElseIf Turning light changes to red from permissive or green Then
        Set next turning departure to a large number as no cars can depart turning until
        after the next light change ( $t(3) = \text{Large}$  );
    ElseIf Turning light changes to permissive from green or red Then
        Initialise next turning departure time to now ( $t(3) = Now$ );
        Calculate time until next opposing vehicle arrival (
         $t_{oppose} = \lambda_{oppose} \ln(1/(1 - rand))$ );

```

```

While  $t(3) < Now + \text{Time until turning light changes to red}$ 
    If  $\text{Time unit next opposing arrival} > \text{Minimum time gap to cross}$  Then
        Next turning departure is can occur before the next opposing
        vehicle arrives, so update next turning arrival time and exit
        while loop ( $t(3) = t(3) + 1/T_{dept}$ ); Exit While
    ElseIf  $\text{Next opposing arrival} < \text{Minimum time gap to cross}$  Then
        Increase earliest time for next turning departure by the time
        until the next opposing arrival ( $t(3) = t(3) + t_{oppose}$ );
    EndIf
EndWhile
EndIf
Update next light change time ( $t(4) = Now + \text{Config}(3, State)$ );
EndIf

```

APPENDIX B

Simulation Model Code

```
function
[t_final,S_final,T_final,C_track,t_max,Block_Overflow]=Main(Plot_Mode,T_max
)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Description %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% This model represents a simple situation of cars arriving at a set of
% traffic light with the option of continuing straight, or turning right
% (no left turn being considered at this stage). There is only one lane for
% traffic going straight. This model does incorporate the situation in
% which the traffic lights turn green periodically. It assumes that traffic
% arrives at random (modelled using a Weibull distribution with shape
% parameter 1 and scale parameter lambda). Traffic departs at a constant
% rate, with times taken to react to a green light, and travel the length
% of the queue averaged out (i.e. implicitly incorporated into the average
% rate). When a light turns green the first waiting car departs immediately
% (no delay). Permissive turning is considered.

% Assumptions:
% 1. One noteworthy assumption is that upon a light change to green, the
% first car goes immediately, and without hesitation. However if the light
% goes permissive, then the first car will wait for 1/T_dept until it goes.
% This is not completely unreasonable as there is likely to be more
% hesitation to assess the situation with permissive, however it may be
% more ideal to introduce a specific delay factor for that purpose.
% 2. When the light changes from permissive to green it is not easy to
% determine when the previous turning event was under permissive, so we
% just delay the departure of the first car under green to 1/T_dept. Again
% this is not completely unjustified as a turning car is likely to delay
% while they ensure that the oncoming cars are indeed stopping.

% Called By - SimulateDesign.m

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Problem Parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
global lambda
global lambda_oppose
global S_dept
global T_dept
global Config
global min_time_gap
global testing
global dt_p_remainder
global M_track
global T_max

% testing = parameter that allows us to switch to a deterministic case for
% the purpose of testing. If testing=1 then we are going deterministic,
% while if testing=0 we are in random mode.
testing=0;
```

```

force=2; % not important but don't change - just ensures that in the
deterministic setting the first car goes straight and then they alternate.
% lambda = average time between cars arriving.
lambda=4.5; % seconds.
% Lambda_oppose = average time between cars arriving and going straight in
the opposing
% direction (relevant to permissive turning).
lambda_oppose=6; % seconds.
% min_time_gap = Number of seconds between opposing traffic required for a
turning car to make a permissive turn (seconds).
min_time_gap=4.1; % seconds.
% turn_prob = probability that an arriving car will turn.
turn_prob=0.7;
% t_max = simulation duration.
t_max=13000*120; % seconds.
if t_max>10^16
    display('Need to increase the size of the large number setting or the
results will fail')
end
% T_max = maximum number of cars in the turning lane.
T_max=0;
% S_dept = departure rate of cars going straight (cars/second).
S_dept=1;
% T_dept = departure rate of cars turning (cars/second).
T_dept=1;
% Config = A matrix containing the sequence of operational states of the
intersection. Each column specifies a state. Row 1 indicates whether the
straight light is red (=0) or green (=1), row 2 indicates whether the
turning light is red, green or permissive (=2), and the bottom row
indicates the state duration.

%Config=[0 0 0 ; 0 0 0 ; 0 0 0];

% Start_State = An index indicating the state of the system at the start of
the simulation. The index refers to the column number of the Config
matrix.
Start_State=1;
%Start_Phase = Fraction of the Start_State that has already passed at the
time the simulation starts (i.e. a number between 0 and 1).
Start_Phase =0;
% S = number of cars queued in straight lane. We assume that all cars
initially in the straight lane want to go straight. Need to manually
modify initialisation of 'M_track' if this is not the case.
S=0; % initial value set here.
% T = number of cars queued in turning lane.
T=0; % initial value set here. Must be <=T_max.
% t_now = time since the start of the simulation.
t_now=0; % seconds.
% Plot_Mode = Controls if a plot is to be produced. Typically, if Main3 is
being
called on its own, then Mode=1 will ensure that plots are produced for
that individual simulation run. If Main3 is being called from Simulate.m,
then Mode=0 will suppress the plots from Main3 while Simulate.m constructs
a single plot of multiple simulation runs.

% Need to track the number of cycles and the number of blocks and
overflows. We will use Nc to count the number of cycles, Nb1 to count the
number of cycles in which a T vehicle is blocked from entering the
turning lane by an S vehicle, Nb2 to count the number of cycles in which

```

```

% a T vehicle is blocked from entering the turning lane, and T=0 with the
light green (i.e. this
% actually is real hold up/delay), No1 to count the number of cycles in
% which there are T vehicles in the S lane, No2 to count the number of
% cycles in which the front vehicle in the S lane is a T vehicle and the
% light is green (i.e. a real hold up). The corresponding ib1, ib2, io1 and
% io2 indicators are used to ensure that a cycle is only counted in each
% condition once.
Nc=1;
Nb1=0;
Nb2=0;
No1=0;
No2=0;
ib1=0;
ib2=0;
io1=0;
io2=0;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Step 1 (Check): If we are wanting plots, plot the traffic light colours
% as a check to make sure the cycles are as intended.
if Plot_Mode==1
    t(1)=0;
    S_check(1)=Config(1,Start_State);
    T_check(1)=Config(2,Start_State);
    t_next=min((1-Start_Phase)*Config(3,Start_State),t_max);
    t(2)=t_next;
    S_check(2)=S_check(1);
    T_check(2)=T_check(1);
    count=2;
    State=Start_State;
    while t_next<=t_max
        t(count+1)=t(count);
        State=State+1;
        if State>size(Config,2)
            State=1;
        end
        S_check(count+1)=Config(1,State);
        T_check(count+1)=Config(2,State);
        if t_next==t_max
            t_next=t_max+1; % Want to exit while loop if we have already
treated t_max.
        else
            t_next=min(t_next+Config(3,State),t_max);
            S_check(count+2)=S_check(count+1);
            T_check(count+2)=T_check(count+1);
            t(count+2)=t_next;
            count=count+2;
        end
    end
    figure
    plot(t,S_check,'b',t,T_check,'r')
    ylim([0,3])
    xlabel('Time (s)')
    ylabel('Light colour')
    title('Red = 0, Green = 1, Permissive = 2')
    clear count
end

```

```

% Step 2: Initialise the Simulation.
% Start tracking vectors.
% M_track = Indicator vector to track which cars in the S lane are wanting
% to be in the T lane. 0 denotes wanting to be in S, 1 denotes wanting to
% be in T.
% S_track, T_track, and t_track = Vectors that store the length of each
% queue (S_track, straight, T_track, turning) at each event time stored in
% t_track. That is, S,T,t_now are scalars, while S_track, T_track and
% t_track are ultimately vectors.
S_track=zeros(1,t_max);
T_track=zeros(1,t_max);
t_track=zeros(1,t_max);
S_track(1)=S;
T_track(1)=T;
t_track(1)=t_now;
S_count=2;
T_count=2;
t_count=2;
if S_track(1)>0
    M_track=zeros(1,S); % Assuming that all cars originally in the S lane
    want to go straight. Need to manually modify if this is not the case.
end
% C_track = Matrix to record the arrival sequence of cars, their arrival
% time and departure time, in order to determine the wait time
% distribution. The matrix will be initialised as empty, and will be
% constructed as cars arrive. The first column will record the type of car
% (1 = Straight, 2 = Turning), the second column will record the arrival
% time, while the third column will record the departure time. Each row
% will correspond uniquely to one car.
% For the purpose of pre-allocating for speed, we will allow for 1.1 of
% t_max/lambda cars
C_track=zeros(round(1.1*t_max/lambda),3);
C_count=1;

% Set initial value for the next arrival time.
if testing==1
    a=1-exp(-1);
else
    a=rand(1);
end
dt=lambda*log(1/(1-a));

% Set the initial value for the wait time for the next permissive crossing.
dt_p=0;
while dt_p<max(Config(3,:))
    if testing==1
        b=lambda_oppose;
    else
        b=lambda_oppose*log(1/(1-rand(1))); % b is the time until the next
        opposing car arrives
    end
    if b>min_time_gap
        % dt_p_remainder keeps track of when the next car is arriving to
        % correctly consider multiple cars crossing between two on-coming
        cars.
        dt_p_remainder=b-1/T_dept; %(i.e. the time until the next opposing
        car arrives minus the time for the current car to clear the way).
        break
    end
end

```

```

        else
            dt_p=dt_p+b;
        end
    end

% Define next event time vector.
clear t % Clear in case it was used in the plotting.
% t = Row vector of next event times. The columns represent the time of the
% next: 1. new arrival; 2. straight departure; 3. turning departure;
% 4. Next light state change. (seconds).
% Note: We do not need to worry if T>0 and/or S>0 when initialising t. If
% they happen to be zero then this will be dealt with during the
% simulation, and the event time adjusted appropriately.
t=10^16*ones(1,4);
t(1)=t_now+dt;
t(4)=t_now+(1-Start_Phase)*Config(3,Start_State);

if Config(1,Start_State)==0 % Straight red
    t(2)=10^16;
elseif Config(1,Start_State)==1 % Straight green
    t(2)=t_now;
end

if Config(2,Start_State)==0 % Turning red
    t(3)=10^16;
elseif Config(2,Start_State)==1 % Turning green
    t(3)=t_now;
elseif Config(2,Start_State)==2 % Turning permissive
    t(3)=t_now+dt_p+1/T_dept;
end

% Step 3: Run the simulation.
[t_now,Mode]=min(t);
State=Start_State;
C_track_S_index=1; % This keeps track of the index of the previous straight
car to leave, so that when C_track is updated we do not need to re-search
from the first car that arrived.
C_track_T_index=1; % Similarly for turning.
while t_now<t_max
    if Mode==1 % New arrival
        if testing==1
            % We can force an alternation between straight and turning
            if force==1
                force=2;
            else
                force=1;
            end
            a=2;
        else
            force=0;
            a=rand(1);
        end
        if a<=turn_prob || force==2 % Turning arrival
            C_track(C_count,:)= [2 t_now t_max+1];
            C_count=C_count+1;
            if T<T_max && S<T_max % Goes straight into turning lane.
                T=T+1;
            else % Turning lane full or blocked - goes into straight lane.
                S=S+1;
                if S==1

```

```

        M_track=1;
    else
        M_track=[M_track 1];
    end
    if io1==0
        No1=No1+1;
        io1=1;
    end
end
else % Straight arrival
    C_track(C_count,:)= [1 t_now t_max+1];
    C_count=C_count+1;
    S=S+1;
    if S==1
        M_track=0;
    else
        M_track=[M_track 0];
    end
    if S>=T_max && ib1==0
        Nb1=Nb1+1;
        ib1=1;
    end
end
S_track(S_count)=S;
T_track(T_count)=T;
t_track(t_count)=t_now;
S_count=S_count+1;
T_count=T_count+1;
t_count=t_count+1;
% Update Time of Current Event
if testing==1
    a=1-exp(-1);
else
    a=rand(1);
end
t(1)=t_now+lambda*log(1/(1-a));
elseif Mode==2 % Straight departure
    % Need to consider the case that a car wanting to turn can now move
    % into the turning lane because it is within the first T_max of the
    % straight moving cars.
    if S>0 % Cars currently in straight lane.
        if M_track(1)==0 % No blocking - first car in straight lane
            wants to go straight.
            temp=M_track(2:S);
            S=S-1;
            clear M_track
            M_track=temp;
            clear temp
            % Record departure time for departing car
            for i=C_track_S_index:size(C_track,1)
                if C_track(i,1)==1 && C_track(i,3)==t_max+1
                    C_track(i,3)=t_now;
                    C_track_S_index=i+1;
                    break
                end
            end
            % Shift any possible cars to the turning lane.
            if S>=T_max
                while T<T_max && S>=T_max
                    if M_track(T_max)==1 % T_max car wants to be in
turning lane.

```

```

        T=T+1;
        if S>T_max
            temp=[M_track(1:T_max-1)
M_track(T_max+1:S)];
        else
            temp=M_track(1:T_max-1);
        end
        S=S-1;
        clear M_track
        M_track=temp;
        clear temp
        if T==1
            t(3)=t_now; % If a car is shifted to an
empty turning lane we need to see if it can immediately move on.
        end
        else
            break
        end
    end
end
S_track(S_count)=S;
T_track(T_count)=T;
t_track(t_count)=t_now;
S_count=S_count+1;
T_count=T_count+1;
t_count=t_count+1;
% Update Time of Current Event
t(2)=t_now+1/S_dept;
else
    % If the front car wants to turn then they will hold up
    % everyone else in the straight lane until there is an
    % option to move into the turn lane. We will send an
    % exception to Event.m to set the next straight
    % departure considered to be just after the next
    % turning departure.
    if io2==0 % Keep track of hold up due to overflow.
        No2=No2+1;
        io2=1;
    end
    % Update Time of Current Event
    t(2)=t(3)+10^(-6);
end
else
    % If there are no cars in the straight lane then obviously
    % nothing will happen until another car has arrived. We will
    % send an exception to Event.m to set the next straight
    % departure considered to be just after the next arrival.
    % Update Time of Current Event
    t(2)=t(1)+10^(-6);
end
elseif Mode==3 % Turning departure.
    if T>0
        T=T-1;
        % Record departure time for departing car
        for i=C_track_T_index:size(C_track,1)
            if C_track(i,1)==2 && C_track(i,3)==t_max+1
                C_track(i,3)=t_now;
                C_track_T_index=i+1;
                break
            end
        end
    end
end

```

```

% If the turning lane had been full prior to the removal of
% the current car, then we need to allow cars in the
% straight lane to move into the turning lane if required.
if S>0 && T==T_max-1
    for i=1:min(S,T_max)
        if M_track(i)==1
            T=T+1;
            if i==1
                temp=M_track(2:S);
            elseif i>1 && i<S
                temp=[M_track(1:i-1) M_track(i+1:S)];
            else
                temp=M_track(1:i-1);
            end
            S=S-1;
            clear M_track
            M_track=temp;
            clear temp
            break
        end
    end
end
S_track(S_count)= S;
T_track(T_count)=T;
t_track(t_count)=t_now;
S_count=S_count+1;
T_count=T_count+1;
t_count=t_count+1;
% Update Time of Current Event
if Config(2,State)==2 % permissive
    dt_p=0;
    count=0;
    while dt_p<max(Config(3,:))
        if count==0
            b=dt_p_remainder;
            count=1;
        else
            if testing==1
                b=lambda_oppose;
            else
                b=lambda_oppose*log(1/(1-rand(1))));
            end
        end
        if b>min_time_gap
            dt_p_remainder=b-1/T_dept;
            break
        else
            dt_p=dt_p+b;
        end
    end
    t(3)=t_now+dt_p+1/T_dept;
else
    t(3)=t_now+1/T_dept;
end
else
    % If there are no cars in the turning lane then obviously
    % nothing will happen until another car has arrived. We will
    % send an exception to Event.m to set the next turning
    % departure considered to be just after the next arrival.
    if sum(M_track)>0 && ib2==0
        Nb2=Nb2+1;
    end
end

```

```

        ib2=1;
    end
    % Update Time of Current Event
    if Config(2,State)==2 % Permissive
        dt_p=0;
        count=0;
        while dt_p<max(Config(3,:))
            if count==0
                b=dt_p_remainder;
                count=1;
            else
                if testing==1
                    b=lambda_oppose;
                else
                    b=lambda_oppose*log(1/(1-rand(1)));
                end
            end
            if b>min_time_gap
                dt_p_remainder=b-1/T_dept;
                break
            else
                dt_p=dt_p+b;
            end
        end
        t(3)=min(t(1),t(2))+10^(-6)+dt_p+1/T_dept;
    else
        t(3)=min(t(1),t(2))+10^(-6);
    end
end
elseif Mode==4 % Traffic Light Change.
    Prior_State=State;
    State=State+1;
    if State>size(Config,2)
        State=1;
    end
    % For the sake of counting cycles, overflows and blocks
    if State==Start_State
        Nc=Nc+1;
        ib1=0;
        ib2=0;
        io1=0;
        io2=0;
    end
    if Config(1,Prior_State)==0 && Config(1,State)==1 % Straight light
turns from red to green
        t(2)=t_now+10^(-6); % Need to make sure that this does not look
like the previous event.
    elseif Config(1,Prior_State)==1 && Config(1,State)==0 % Straight
light turns from green to red
        t(2)=10^16;
    end
    if Config(2,Prior_State)~=1 && Config(2,State)==1 % Turning light
turns from red or permissive to green
        if t(3)==10^16 % From red to green
            t(3)=t_now+10^(-6); % Need to make sure that this does not
look like the previous event.
        else % From permissive to green we need to consider how recent
the previous event was.
            t(3)=t_now+1/T_dept;
        end
    end
end

```

```

        elseif Config(2,Prior_State)~=0 && Config(2,State)==0 % Turning
light turns from green or permissive to red
            t(3)=10^16;
        elseif Config(2,Prior_State)~=2 && Config(2,State)==2 % Turning
light turns from red or green to permissive
            dt_p=0;
            while dt_p<max(Config(3,:))
                if testing==1
                    b=lambda_oppose;
                else
                    b=lambda_oppose*log(1/(1-rand(1)));
                end
                if b>min_time_gap
                    dt_p_remainder=b-1/T_dept;
                    break
                else
                    dt_p=dt_p+b;
                end
            end
            t(3)=t_now+dt_p+1/T_dept; % Unlike a traffic light change,
there is necessarily to delay of 1/T_dept before the first car goes.
        end
        % Update Time of Current Event
        t(4)=t_now+Config(3,State);
    end
    % The following section of code is somewhat optional. The idea is that
we
    % want to avoid situations in which a change in light preceeds a
departure,
    % or an arrival by a trivial margin (e.g. 10^-4 seconds). What we will
do
    % is to check that this is not the case, and if so, will reduce the
time
    % values of the nearest event to equal the light change time. This will
    % ensure the arrival or departure is selected as the next event (due to
    % index precedence).
    % by
    [t_now,Mode]=min(t);
    [min_2,Mode_2]=min(t(1:3));
    if Mode==4
        if min_2-t_now<10^(-3)
            t(Mode_2)=t_now;
            Mode=Mode_2;
        end
    end
end
C_temp=C_track;
clear C_track
C_track=C_temp(1:C_count-1,:);
clear C_temp

S_track(S_count)= S;
T_track(T_count)=T;
t_track(t_count)=t_now;

% Process Results
% We only want to report the level at the end of an event time period.
count=0;
t_final_temp=zeros(1,t_count);
S_final_temp=zeros(1,t_count);
T_final_temp=zeros(1,t_count);

```

```

for i=1:t_count
    if i==1
        count=count+1;
    else
        if abs(t_track(i)-t_track(i-1))>10^(-1)
            count=count+1;
        end
    end
    t_final_temp(count)=t_track(i);
    S_final_temp(count)=S_track(i);
    T_final_temp(count)=T_track(i);
end
t_final=t_final_temp(1:count);
S_final=S_final_temp(1:count);
T_final=T_final_temp(1:count);

if Plot_Mode==1
    % Plot Results

    % This next section ensures sharp jumps rather than slopes in the plot.
    t1=zeros(2*count-1,1);
    S1=zeros(2*count-1,1);
    T1=zeros(2*count-1,1);
    for i=1:count
        t1(2*i-1)=t_final(i);
        S1(2*i-1)=S_final(i);
        T1(2*i-1)=T_final(i);
    end
    for i=1:count-1
        t1(2*i)=t1(2*i+1);
        S1(2*i)=S1(2*i-1);
        T1(2*i)=T1(2*i-1);
    end

    figure
    plot(t1,S1,'b',t1,T1,'r');
    xlabel('Time (s)')
    ylabel('Number of Cars')
end

Block_Overflow=[Nc Nb1 Nb2 No1 No2];

```

```

function [t_out,Exception]=Event(t_in,Exception,State)

```

```

global lambda
global lambda_oppose
global S_dept
global T_dept
global Config
global min_time_gap
global testing
global dt_p_remainder

```

```

% t_in = Row vector of current next event times. The columns represent the
% time of the next: 1. new arrival; 2. straight departure; 3. turning
departure;
% 4. Next light state change. (seconds). The event
% corresponding to the minimum time is the event that has just occurred and
% needs updating.

```

```

t_out=t_in;
[min_t,Mode]=min(t_in); % Identify the event that happened last so we can
update the next time for that event.

if Mode==1
    if testing==1
        a=1-exp(-1);
    else
        a=rand(1);
    end
    t_out(1)=min_t+lambda*log(1/(1-a));
elseif Mode==2
    if Exception==0
        t_out(2)=min_t+1/S_dept;
    elseif Exception==1
        % Under Exception=1, the next possible time to consider a straight
        % departure is after the front car has a chance to move out of the
        % way and into the turning lane.
        t_out(2)=t_in(3)+10^(-6);
    elseif Exception==2
        % Under Exception=2, the next possible time to consider a straight
        % departure is after the next arrival (i.e. there are currently no
        % cars in the S lane).
        t_out(2)=t_in(1)+10^(-6);
    end
elseif Mode==3
    if Exception==0
        if Config(2,State)==2 % permissive
            dt_p=0;
            count=0;
            while dt_p<max(Config(3,:))
                if count==0
                    b=dt_p_remainder;
                    count=1;
                else
                    if testing==1
                        b=lambda_oppose;
                    else
                        b=lambda_oppose*log(1/(1-rand(1)));
                    end
                end
                if b>min_time_gap
                    dt_p_remainder=b-1/T_dept;
                    break
                else
                    dt_p=dt_p+b;
                end
            end
            t_out(3)=min_t+dt_p+1/T_dept;
        else
            t_out(3)=min_t+1/T_dept;
        end
    elseif Exception==2
        % Under Exception=2, the next possible time to consider a turning
        % departure is after the next arrival or after the next straight
        % car leaves (i.e. there are currently no cars in the T lane).
        if Config(2,State)==2 % Permissive
            dt_p=0;
            count=0;
            while dt_p<max(Config(3,:))

```

```

        if count==0
            b=dt_p_remainder;
            count=1;
        else
            if testing==1
                b=lambda_oppose;
            else
                b=lambda_oppose*log(1/(1-rand(1)));
            end
        end
        if b>min_time_gap
            dt_p_remainder=b-1/T_dept;
            break
        else
            dt_p=dt_p+b;
        end
    end
    t_out(3)=min(t_in(1),t_in(2))+10^(-6)+dt_p+1/T_dept;
else
    t_out(3)=min(t_in(1),t_in(2))+10^(-6);
end
end
elseif Mode==4
    t_out(4)=min_t+Config(3,State);
end
Exception=0;

% The following section of code is somewhat optional. The idea is that we
% want to avoid situations in which a change in light preceeds a departure,
% or an arrival by a trivial margin (e.g. 10^-4 seconds). What we will do
% is to check that this is not the case, and if so, will reduce the time
% values of the nearest event to equal the light change time. This will
% ensure the arrival or departure is selected as the next event (due to
% index precedence).
% by
[min_1,Mode_1]=min(t_out);
[min_2,Mode_2]=min(t_out(1:3));
if Mode_1==4
    if min_2-min_1<10^(-3)
        t_out(Mode_2)=t_out(Mode_1);
    end
end
end

function
[Store1,Store2,Store3]=Performance_Metrics(t_final,S_final,T_final,C_track,
t_max,Block_Overflow)
% This function will accept the outputs of Main.m, and use them to
% calculate performance metrics for the intersection. The metrics being
% considered are:
% 1. Time spent waiting in a queue.
% 2. Length of a queue.

% Queue Lengths
S_max=max(S_final); % Maximum straight queue length.
T_max=max(T_final); % Maximum Turning queue length.
S=linspace(0,S_max,S_max+1); % List of possible straight queue lengths.
T=linspace(0,T_max,T_max+1); % List of possible turning queue lengths.
tS=zeros(S_max+1,1); % Vector to store the total time for each straight
queue length.
tT=zeros(T_max+1,1); % Vector of store the total time for each turning
queue length.
t_now=0;

```

```

S_now=S_final(1);
for i=2:size(S_final,2);
    if S_final(i)~=S_final(i-1) || i==size(S_final,2)
        tS(S_now+1)=tS(S_now+1)+t_final(i)-t_now;
        t_now=t_final(i);
        S_now=S_final(i);
    end
end

t_now=0;
T_now=T_final(1);
for i=2:size(T_final,2);
    if T_final(i)~=T_final(i-1) || i==size(T_final,2)
        tT(T_now+1)=tT(T_now+1)+t_final(i)-t_now;
        t_now=t_final(i);
        T_now=T_final(i);
    end
end

%figure
%bar(S,tS./sum(tS))
%xlabel('Straight Queue Length')
%ylabel('Probability')
%figure
%bar(T,tT./sum(tT))
%xlabel('Turning Queue Length')
%ylabel('Probability')

% Statistics
Store1=cell(4,3);
Store1(1,2)={'Straight'};
Store1(1,3)={'Turning'};
Store1(2,1)={'Mean Queue Length'};
Store1(3,1)={'Standard Deviation'};
Store1(4,1)={'Maximum Length'};

meanS=dot(S,tS./sum(tS));
meanT=dot(T,tT./sum(tT));
SdevS=sqrt(dot(S.^2,tS./sum(tS))-meanS^2);
SdevT=sqrt(dot(T.^2,tT./sum(tT))-meanT^2);

Store1(2,2)={meanS};
Store1(3,2)={SdevS};
Store1(4,2)={S_max};
Store1(2,3)={meanT};
Store1(3,3)={SdevT};
Store1(4,3)={T_max};

% Time in Queue
N=size(C_track,1); % Number of Cars in the system.
% Cars that remain in the queue at the end of the simulation are not going
% to be considered as they would bias the queue time downward. As long as
% the simulation duration t_max is large enough, this should not be a
% problem. There are ways to incorporate these cars into the statistical
% analysis in the future if that is considered necessary.
neglected_cars=0;
for i=1:N
    if C_track(i,3)>t_max
        C_track(i,1)=0;
        neglected_cars=neglected_cars+1;
    end
end

```

```

        end
    end
    n=N-neglected_cars; % Number of cars being considered.
    S_cars_temp=zeros(1,N); % Stores the wait times for the straight cars.
    T_cars_temp=zeros(1,N); % Stores the wait times for the turning cars.
    S_count=0;
    T_count=0;
    for i=1:N
        if C_track(i,1)==1
            S_count=S_count+1;
            S_cars_temp(S_count)=C_track(i,3)-C_track(i,2);
        elseif C_track(i,1)==2
            T_count=T_count+1;
            T_cars_temp(T_count)=C_track(i,3)-C_track(i,2);
        end
    end
    S_cars=S_cars_temp(1:S_count);
    T_cars=T_cars_temp(1:T_count);

    % Statistics
    Store2=cell(4,4);
    Store2(1,2)={'Straight'};
    Store2(1,3)={'Turning'};
    Store2(1,4)={'Overall'};
    Store2(2,1)={'Number of Cars'};
    Store2(3,1)={'Mean Wait Time'};
    Store2(4,1)={'Standard Deviation'};

    nS=size(S_cars,2);
    nT=size(T_cars,2);
    meanS=sum(S_cars)/nS;
    meanT=sum(T_cars)/nT;
    SdevS=sqrt(sum((S_cars-meanS*ones(1,nS)).^2)/(nS-1));
    SdevT=sqrt(sum((T_cars-meanT*ones(1,nT)).^2)/(nT-1));

    All_cars=[S_cars T_cars];
    meanO=sum(All_cars)/n;
    SdevO=sqrt(sum((All_cars-meanO*ones(1,n)).^2)/(n-1));

    Store2(2,2)={nS};
    Store2(3,2)={meanS};
    Store2(4,2)={SdevS};
    Store2(2,3)={nT};
    Store2(3,3)={meanT};
    Store2(4,3)={SdevT};
    Store2(2,4)={n};
    Store2(3,4)={meanO};
    Store2(4,4)={SdevO};

    Store3=cell(3,6);
    Store3(1,2)={'Cycles'};
    Store3(1,3)={'Blocking Cycles'};
    Store3(1,4)={'Overflow Cycles'};
    Store3(1,5)={'Blocking Cycles with delay'};
    Store3(1,6)={'Overflow Cycles with delay'};
    Store3(2,1)={'Number'};
    Store3(3,1)={'Percentage'};
    Store3(2,2)={Block_Overflow(1)};
    Store3(2,3)={Block_Overflow(2)};
    Store3(2,4)={Block_Overflow(4)};

```

```

Store3(2,5)={Block_Overflow(3)};
Store3(2,6)={Block_Overflow(5)};
Store3(3,3)={round(1000*Block_Overflow(2)/Block_Overflow(1))/10};
Store3(3,4)={round(1000*Block_Overflow(4)/Block_Overflow(1))/10};
Store3(3,5)={round(1000*Block_Overflow(3)/Block_Overflow(1))/10};
Store3(3,6)={round(1000*Block_Overflow(5)/Block_Overflow(1))/10};

%Simulate Design
tic,
T_max=0;
Block=100;
Overflow=100;
while Block>=5 || Overflow>=5
    T_max=T_max+1;
    display(T_max)
    [t_final,S_final,T_final,C_track,t_max,Block_Overflow]=Main(0,T_max);
    Block=Block_Overflow(4)/Block_Overflow(1)*100;
    Overflow=Block_Overflow(5)/Block_Overflow(1)*100;
end

[Store1,Store2,Store3]=Performance_Metrics(t_final,S_final,T_final,C_track,
t_max,Block_Overflow);

display(Store1)
display(Store2)
display(Store3)

display(T_max),toc

```

APPENDIX C

Operation Centre Reports (MRWA)

04-NOV-2014 17:09:36 441 IP1.2. LCNF CL171+2	A	D	E	G
A <MIN@1 GRN@9 MX@68 P^D:YEL@70 RED@73 MX0 ALO CG44>49 PT76	76			
D MIN@1 GRN@7 MX@27 P^E:YEL@29 RED@34 MX0 ALO CG64>69 PT35		35		
E MIN@1 W2@7 GRN@9 MX@27 P^G:YEL@29 RED@34 MX0 ALO CG84>89 PT35			35	
G MIN@1 GRN@9 MX@20 P^A:YEL@22 RED@27 MX0 ALO CG0>3 PT28				28
04-NOV-2014 17:04:06 441 IP1.2. LCNF CL173+0				
A <MIN@1 GRN@9 MX@65 P^D:YEL@67 RED@72 MX0 ALO CG41>47 PT73	73			
D MIN@1 GRN@7 MX@31 P^E:YEL@33 RED@38 MX0 ALO CG64>69 PT39		39		
E MIN@1 GRN@9 MX@27 P^G:YEL@29 RED@34 MX0 ALO CG84>89 PT35			35	
G MIN@1 GRN@9 MX@20 P^A:YEL@22 RED@27 MX0 ALO CG0>3 PT28				28
04-NOV-2014 17:07:01 441 IP1.2. LCNF CL173+2				
A <MIN@1 GRN@9 MX@69 P^D:YEL@71 RED@76 MX0 ALO CG44>50 PT77	77			
D MIN@1 GRN@7 MX@27 ECG@28 YEL@29 RED@34 MX0 ALO CG64>70 PT35		35		
E MIN@1 GRN@9 MX@27 P^G:YEL@29 RED@34 MX0 ALO CG84>90 PT35			35	
G MIN@1 GRN@9 MX@20 P^A:YEL@22 RED@27 MX0 ALO CG0>7 PT28				28
04-NOV-2014 17:09:36 441 IP1.2. LCNF CL171+2				
A <MIN@1 GRN@9 MX@64 P^D:YEL@67 RED@71 MX0 ALO CG41>48 PT72	72			
D MIN@1 GRN@7 MX@27 P^E:YEL@29 RED@34 MX0 ALO CG61>69 PT35		35		
E MIN@1 GRN@9 MX@27 P^G:YEL@29 RED@34 MX0 ALO CG82>90 PT35			35	
G MIN@1 GRN@9 MX@23 P^A:YEL@25 RED@30 MX0 ALO CG0>8 PT31				31
04-NOV-2014 17:12:49 441 IP1.2. LCNF CL172-2				
A <MIN@1 GRN@9 MX@67 P^D:YEL@69 RED@74 MX0 ALO CG44>51 PT75	75			
D MIN@1 GRN@7 MX@26 P^E:YEL@28 RED@33 MX0 ALO CG64>71 PT34		34		
E MIN@1 GRN@9 MX@26 P^G:YEL@28 RED@33 MX0 ALO CG84>91 PT34			34	
G MIN@1 GRN@9 YEL@17 RED@22 MX4 AL1 CG97>4 PT23				23
04-NOV-2014 17:15:35 441 IP1.2. LCNF CL174+0				
A <TG:MIN@1 GRN@9 MX@73 P^D:YEL@75 RED@80 MX0 ALO CG44>51 PT81	81			
D MIN@1 GRN@7 MX@27 P^E:YEL@29 RED@34 MX0 ALO CG64>71 PT35		35		
E MIN@1 GRN@9 MX@27 P^G:YEL@29 RED@34 MX0 ALO CG84>91 PT35			35	
G MIN@1 GRN@9 MX@20 P^A:YEL@22 RED@27 MX0 ALO CG0>7 PT28				28
04-NOV-2014 17:18:34 441 IP1.2. LCNF CL174+0				
A <MIN@1 GRN@9 MX@68 P^D:YEL@70 RED@75 MX0 ALO CG44>51 PT76	76			
D MIN@1 GRN@7 MX@27 P^E:YEL@29 RED@34 MX0 ALO CG64>71 PT35		35		
E MIN@1 W2@7 GRN@9 MX@27 P^G:YEL@29 RED@34 MX0 ALO CG84>91 PT35			35	
G MIN@1 GRN@9 MX@20 P^A:YEL@22 RED@27 MX0 ALO CG0>7 PT28				28
04-NOV-2014 17:21:28 441 IP1.2. LCNF CL173+0				
A <MIN@1 GRN@9 MX@64 P^D:YEL@66 RED@71 MX0 ALO CG42>48 PT72	72			
D MIN@1 GRN@7 MX@27 P^E:YEL@29 RED@34 MX0 ALO CG62>69 PT35		35		
E MIN@1 GRN@9 MX@27 P^G:YEL@29 RED@34 MX0 ALO CG82>89 PT35			35	
G MIN@1 GRN@9 YEL@17 RED@22 MX8 AL1 CG96>3 PT23				23
04-NOV-2014 17:24:13 441 IP1.2. LCNF CL173+0				
A <TG:MIN@1 GRN@9 MX@71 P^D:YEL@73 RED@78 MX0 ALO CG41>48 PT79	79			
D MIN@1 GRN@7 MX@27 P^E:YEL@29 RED@34 MX0 ALO CG61>68 PT35		35		
E MIN@1 GRN@9 MX@27 P^G:YEL@29 RED@34 MX0 ALO CG82>89 PT35			35	
G MIN@1 GRN@9 MX@20 P^A:YEL@22 RED@27 MX0 ALO CG98>3 PT28				28
04-NOV-2014 17:27:10 441 IP1.2. LCNF CL175-2				
A <MIN@1 GRN@9 MX@70 P^D:YEL@72 RED@77 MX0 ALO CG43>48 PT78	78			
D MIN@1 GRN@7 MX@27 P^E:YEL@29 RED@34 MX0 ALO CG63>69 PT35		35		

04-NOV-2014 17:09:36	441 IP1.2.	LCNF CL171+2	A	D	E	G
A	MIN@1 W1@7 GRN@9 MX@68 P@D:YEL@70 RED@75 MX0 ALO CG44>49 FT76		76			
D	MIN@1 GRN@7 MX@27 P@E:YEL@29 RED@34 MX0 ALO CG64>69 FT35			35		
E	MIN@1 W2@7 GRN@9 MX@27 P@G:YEL@29 RED@34 MX0 ALO CG84>89 FT35				35	
G	MIN@1 GRN@9 MX@20 P@A:YEL@22 RED@27 MX0 ALO CG0>3 FT28					28
04-NOV-2014 17:04:06	441 IP1.2.	LCNF CL173+0				
A	MIN@1 GRN@9 MX@65 P@D:YEL@67 RED@72 MX0 ALO CG41>47 FT73		73			
D	MIN@1 GRN@7 MX@31 P@E:YEL@33 RED@38 MX0 ALO CG64>69 FT39			39		
E	MIN@1 GRN@9 MX@27 P@G:YEL@29 RED@34 MX0 ALO CG84>89 FT35				35	
G	MIN@1 GRN@9 MX@20 P@A:YEL@22 RED@27 MX0 ALO CG0>3 FT28					28
04-NOV-2014 17:07:01	441 IP1.2.	LCNF CL173+2				
A	MIN@1 GRN@9 MX@69 P@D:YEL@71 RED@76 MX0 ALO CG44>50 FT77		77			
D	MIN@1 GRN@7 MX@27 ECG@28 YEL@29 RED@34 MX0 ALO CG64>70 FT35			35		
E	MIN@1 GRN@9 MX@27 P@G:YEL@29 RED@34 MX0 ALO CG84>90 FT35				35	
G	MIN@1 GRN@9 MX@20 P@A:YEL@22 RED@27 MX0 ALO CG0>7 FT28					28
04-NOV-2014 17:09:36	441 IP1.2.	LCNF CL171+2				
A	MIN@1 GRN@9 MX@64 P@D:YEL@67 RED@71 MX0 ALO CG41>48 FT72		72			
D	MIN@1 GRN@7 MX@27 P@E:YEL@29 RED@34 MX0 ALO CG61>69 FT35			35		
E	MIN@1 GRN@9 MX@27 P@G:YEL@29 RED@34 MX0 ALO CG82>90 FT35				35	
G	MIN@1 GRN@9 MX@23 P@A:YEL@25 RED@30 MX0 ALO CG0>8 FT31					31
04-NOV-2014 17:12:49	441 IP1.2.	LCNF CL172+2				
A	MIN@1 GRN@9 MX@67 P@D:YEL@69 RED@74 MX0 ALO CG44>51 FT75		75			
D	MIN@1 GRN@7 MX@26 P@E:YEL@28 RED@33 MX0 ALO CG64>71 FT34			34		
E	MIN@1 GRN@9 MX@26 P@G:YEL@28 RED@33 MX0 ALO CG84>91 FT34				34	
G	MIN@1 GRN@9 YEL@17 RED@22 MX4 AL1 CG97>4 FT23					23
04-NOV-2014 17:13:35	441 IP1.2.	LCNF CL174+0				
A	TG:MIN@1 GRN@9 MX@73 P@D:YEL@75 RED@80 MX0 ALO CG44>51 FT81		81			
D	MIN@1 GRN@7 MX@27 P@E:YEL@29 RED@34 MX0 ALO CG64>71 FT35			35		
E	MIN@1 GRN@9 MX@27 P@G:YEL@29 RED@34 MX0 ALO CG84>91 FT35				35	
G	MIN@1 GRN@9 MX@20 P@A:YEL@22 RED@27 MX0 ALO CG0>7 FT28					28
04-NOV-2014 17:18:34	441 IP1.2.	LCNF CL174+0				
A	MIN@1 GRN@9 MX@68 P@D:YEL@70 RED@75 MX0 ALO CG44>51 FT76		76			
D	MIN@1 GRN@7 MX@27 P@E:YEL@29 RED@34 MX0 ALO CG64>71 FT35			35		
E	MIN@1 W2@7 GRN@9 MX@27 P@G:YEL@29 RED@34 MX0 ALO CG84>91 FT35				35	
G	MIN@1 GRN@9 MX@20 P@A:YEL@22 RED@27 MX0 ALO CG0>7 FT28					28
04-NOV-2014 17:21:28	441 IP1.2.	LCNF CL173+0				
A	MIN@1 GRN@9 MX@64 P@D:YEL@66 RED@71 MX0 ALO CG42>48 FT72		72			
D	MIN@1 GRN@7 MX@27 P@E:YEL@29 RED@34 MX0 ALO CG62>69 FT35			35		
E	MIN@1 GRN@9 MX@27 P@G:YEL@29 RED@34 MX0 ALO CG82>89 FT35				35	
G	MIN@1 GRN@9 YEL@17 RED@22 MX8 AL1 CG96>3 FT23					23
04-NOV-2014 17:24:13	441 IP1.2.	LCNF CL173+0				
A	TG:MIN@1 GRN@9 MX@71 P@D:YEL@73 RED@78 MX0 ALO CG41>48 FT79		79			
D	MIN@1 GRN@7 MX@27 P@E:YEL@29 RED@34 MX0 ALO CG61>68 FT35			35		
E	MIN@1 GRN@9 MX@27 P@G:YEL@29 RED@34 MX0 ALO CG82>89 FT35				35	
G	MIN@1 GRN@9 MX@20 P@A:YEL@22 RED@27 MX0 ALO CG98>5 FT28					28
04-NOV-2014 17:27:10	441 IP1.2.	LCNF CL175+2				
A	MIN@1 GRN@9 MX@70 P@D:YEL@72 RED@77 MX0 ALO CG43>48 FT78		78			
D	MIN@1 GRN@7 MX@27 P@E:YEL@29 RED@34 MX0 ALO CG63>69 FT35			35		

E	MIN	1	W2	7	GRN	9	MX	27	PAG:YEL	29	RED	34	MX0	ALO	CG83	89	PT33	33	
G	MIN	1	GRN	9	MX	20	PAG:YEL	22	RED	27	MX0	ALO	CG0	5	PT28			28	
04-NOV-2014 17:30:06 441 IP1.2. LCNF CL176-2																			
A	MIN	1	GRN	9	MX	68	PAG:YEL	70	RED	73	MX0	ALO	CG43	48	PT76	76			
D	MIN	1	GRN	7	MX	27	PAG:YEL	29	RED	34	MX0	ALO	CG63	69	PT33		33		
E	MIN	1	GRN	9	MX	27	PAG:YEL	29	RED	34	MX0	ALO	CG83	88	PT33			33	
G	MIN	1	GRN	9	YEL	20	RED	23	MX2	AL1	CG98	3	PT26					26	
04-NOV-2014 17:32:38 441 IP1.2. LCNF CL176+0																			
A	TG:MIN	1	GRN	9	MX	74	PAG:YEL	76	RED	81	MX0	ALO	CG43	50	PT82	82			
D	MIN	1	GRN	7	YEL	19	RED	24	MX10	AL1	CG39	64	PT23				23		
E	TG:1ST	1	MIN	2	GRN	10	MX	37	PAG:YEL	39	RED	44	MX0	ALO	CG83	90	PT43	43	
G	MIN	1	GRN	9	MX	20	PAG:YEL	22	RED	27	MX0	ALO	CG1	5	PT28			28	
04-NOV-2014 17:35:38 441 IP1.2. LCNF CL174+2																			
A	MIN	1	GRN	9	MX	68	PAG:YEL	70	RED	73	MX0	ALO	CG44	48	PT76	76			
D	MIN	1	GRN	7	MX	27	PAG:YEL	29	RED	34	MX0	ALO	CG64	69	PT33		33		
E	MIN	1	GRN	9	MX	27	PAG:YEL	29	RED	34	MX0	ALO	CG84	89	PT33			33	
G	MIN	1	GRN	9	YEL	16	RED	21	MX6	AL1	CG96	2	PT22					22	
04-NOV-2014 17:38:46 441 IP1.2. LCNF CL174+2																			
A	TG:MIN	1	GRN	9	MX	77	PAG:YEL	79	RED	84	MX0	ALO	CG43	51	PT83	83			
D	MIN	1	GRN	7	MX	31	PAG:YEL	33	RED	38	MX0	ALO	CG67	74	PT39		39		
E	MIN	1	GRN	9	YEL	29	RED	34	MX4	AL1	CG87	94	PT33				33		
G	MIN	1	GRN	9	MX	20	YEL	21	RED	26	MX1	AL1	CG3	40	PT27			27	
04-NOV-2014 17:41:52 441 IP1.2. LCNF CL170+0																			
A	TG:MIN	1	W1	7	GRN	9	MX	48	PAG:YEL	50	RED	53	MX0	ALO	CG36	43	PT36	36	
D	MIN	1	GRN	7	YEL	28	RED	33	MX7	AL1	CG36	63	PT34				34		
E	TG:MIN	1	GRN	9	YEL	28	RED	33	MX10	AL1	CG76	83	PT34				34		
G	1ST	1	MIN	2	GRN	10	YEL	23	RED	28	MX2	AL1	CG93	0	PT29			29	
04-NOV-2014 17:44:23 441 IP1.2. LCNF CL170+0																			
A	TG:MIN	1	GRN	9	MX	65	PAG:YEL	67	RED	72	MX0	ALO	CG33	43	PT73	73			
D	MIN	1	GRN	7	MX	30	PAG:YEL	32	RED	37	MX0	ALO	CG37	63	PT38		38		
E	MIN	1	GRN	9	ECG	23	YEL	24	RED	29	MX4	ALO	CG73	82	PT30			30	
G	MIN	1	GRN	9	MX	23	PAG:YEL	25	RED	30	MX0	ALO	CG93	0	PT31			31	
04-NOV-2014 17:47:17 441 IP1.2. LCNF CL172+0																			
A	TG:MIN	1	W1	7	GRN	9	MX	73	PAG:YEL	75	RED	80	MX0	ALO	CG40	48	PT81	81	
D	MIN	1	GRN	7	MX	33	PAG:YEL	35	RED	40	MX0	ALO	CG64	72	PT41		41		
E	MIN	1	W2	7	GRN	9	MX	26	PAG:YEL	28	RED	33	MX0	ALO	CG84	91	PT34		34
G	MIN	1	GRN	9	ECG	21	YEL	22	RED	27	MX3	ALO	CG0	8	PT28			28	
04-NOV-2014 17:50:21 441 IP1.2. LCNF CL173-2																			
A	TG:MIN	1	GRN	9	MX	34	PAG:YEL	36	RED	41	MX0	ALO	CG37	44	PT62	62			
D	MIN	1	GRN	7	MX	36	PAG:YEL	38	RED	43	MX0	ALO	CG62	69	PT44		44		
E	MIN	1	GRN	9	MX	26	YEL	27	RED	32	MX1	AL1	CG82	88	PT33			33	
G	MIN	1	GRN	9	YEL	22	RED	27	MX3	AL1	CG98	4	PT28					28	
04-NOV-2014 17:53:08 441 IP1.2. LCNF CL172+0																			
A	TG:MIN	1	GRN	9	MX	61	PAG:YEL	63	RED	68	MX0	ALO	CG38	44	PT69	69			
D	MIN	1	GRN	7	YEL	23	RED	30	MX10	AL1	CG36	62	PT31				31		
E	TG:1ST	1	MIN	2	GRN	10	YEL	34	RED	41	MX2	AL1	CG80	87	PT42			42	
G	MIN	1	GRN	9	YEL	18	RED	23	MX7	AL1	CG94	1	PT24					24	
04-NOV-2014 17:55:32 441 IP1.2. LCNF CL172+0																			
A	TG:MIN	1	GRN	9	MX	68	PAG:YEL	70	RED	73	MX0	ALO	CG38	46	PT76	76			

D MIN@1 GRN@7 MX@30 P^E:YEL@32 RED@37 MX0 ALO CG60>68 PT38	38				
E MIN@1 GRN@9 MX@27 P^G:YEL@29 RED@34 MX0 ALO CG81>88 PT35		35			
G MIN@1 GRN@9 MX@20 P^A:YEL@22 RED@27 MX0 ALO CG97>5 PT28			28		
04-NOV-2014 17:38:49 441 IP1.2. LCNF CL172-2					
A <MIN@1 GRN@9 MX@72 P^D:YEL@74 RED@79 MX0 ALO CG44>51 PT80	80				
D MIN@1 GRN@7 MX@26 P^E:YEL@28 RED@33 MX0 ALO CG64>71 PT34		34			
E MIN@1 GRN@9 YEL@24 RED@29 MX4 AL1 CG82>89 PT30			30		
G MIN@1 GRN@9 MX@19 P^A:YEL@21 RED@26 MX0 ALO CG97>4 PT27				27	
	1575	747	737	571	3630
	75	36	35	27	173

04-NOV-2014 8:01:35 608 IP2.3. ISOL NF	A	D	E	G	
A <MIN@1 GRN@9 YEL@25 RED@30 AL1 PT31	31				
D LST@1 MIN@2 GRN@10 YEL@44 RED@49 AL1 PT30		30			
E MIN@1 GRN@9 YEL@19 RED@24 AL2 PT25			25		
G LST@1 MIN@2 GRN@10 YEL@13 RED@18 AL1 PT20				20	
04-NOV-2014 8:04:01 608 IP4.3. ISOL NF					
A <MIN@1 GRN@9 YEL@39 RED@44 AL1 PT45	45				
D MIN@1 GRN@9 YEL@32 RED@38 ALO PT39		39			
E MIN@1 GRN@9 YEL@23 RED@28 AL1 PT30			30		
G MIN@1 GRN@9 YEL@21 RED@26 AL2 PT27				27	
04-NOV-2014 8:06:22 608 IP4.3. ISOL NF					
A LST@1 MIN@2 GRN@11 YEL@19 <RED@24 AL1 PT25	25				
D MIN@1 GRN@9 YEL@31 RED@36 AL1 PT37		37			
E LST@1 MIN@2 GRN@10 ECG@12 YEL@13 RED@18 AL1 PT19			19		
G MIN@1 GRN@9 YEL@30 RED@35 AL1 PT37				37	
04-NOV-2014 8:08:20 608 IP4.3. ISOL NF					
A <MIN@1 GRN@9 ECG@18 YEL@19 RED@24 ALO PT25	25				
D MIN@1 GRN@9 ECG@44 YEL@45 RED@50 ALO PT51		51			
E MIN@1 GRN@9 YEL@55 RED@60 AL2 PT61			61		
G LST@1 MIN@3 GRN@10 YEL@31 RED@36 AL2 PT37				37	
04-NOV-2014 8:11:14 608 IP3.3. ISOL NF					
A <MIN@1 W1@7 GRN@9 ECG@34 YEL@35 RED@40 ALO PT41	41				
D MIN@1 GRN@9 YEL@66 RED@71 AL1 PT72		72			
E LST@1 MIN@3 GRN@10 YEL@23 RED@28 AL1 PT30			30		
G MIN@1 GRN@9 YEL@23 RED@28 AL1 PT30				30	
04-NOV-2014 8:14:07 608 IP2.3. ISOL NF					
A <MIN@1 W1@8 GRN@9 YEL@25 RED@30 AL1 PT31	31				
D MIN@1 GRN@9 ECG@40 YEL@42 RED@46 ALO PT47		47			
E MIN@1 GRN@9 ECG@16 YEL@17 RED@22 AL1 PT23			23		
G LST@1 MIN@2 GRN@9 ECG@14 YEL@16 RED@20 AL1 PT21				21	
04-NOV-2014 8:16:09 608 IP2.3. ISOL NF					
A <LST@1 MIN@2 GRN@10 YEL@27 RED@32 AL1 PT33	33				
D LST@1 MIN@2 GRN@10 YEL@31 RED@36 AL1 PT37		37			
E LST@1 MIN@3 GRN@10 ECG@12 YEL@13 RED@18 AL1 PT19			19		

[illegible]

E MIN@1 GRN@9 ECG@18 YEL@20 RED@24 AL0 PT26				26	
G MIN@1 GRN@9 YEL@15 RED@20 AL2 PT21					21
04-NOV-2014 8:41:34 608 IP1.3. ISOL NF					
A <MIN@1 MIN@3 GRN@10 YEL@37 RED@42 AL1 PT43	43				
D MIN@1 GRN@9 YEL@39 RED@44 AL1 PT43		43			
E MIN@1 GRN@10 YEL@25 RED@30 AL1 PT32			32		
G MIN@1 GRN@9 YEL@39 RED@44 AL1 PT46				46	
04-NOV-2014 8:44:40 608 IP3.3. ISOL NF					
A <MIN@1 W1GRN@9 YEL@25 RED@30 AL1 PT31	31				
D LST@1 MIN@2 GRN@10 YEL@32 RED@36 AL2 PT37		37			
E MIN@1 GRN@9 ECG@22 YEL@23 RED@27 AL1 PT29			29		
G MIN@1 GRN@9 YEL@26 RED@31 AL1 PT33				33	
04-NOV-2014 8:47:10 608 IP3.3. ISOL NF					
A <MIN@1 W2@7 GRN@9 YEL@33 RED@38 AL0 PT40	40				
D MIN@1 GRN@8 YEL@33 RED@38 AL1 PT39		39			
E MIN@1 GRN@9 ECG@16 YEL@17 RED@22 AL1 PT23			23		
G LST@1 MIN@2 GRN@11 ECG@27 YEL@29 RED@33 AL1 PT34				34	
04-NOV-2014 8:49:26 608 IP4.3. ISOL NF					
A <LST@1 MIN@2 GRN@10 YEL@28 RED@33 AL1 PT34	34				
D LST@1 MIN@3 GRN@10 YEL@44 RED@49 AL1 PT30		30			
E LST@1 MIN@2 GRN@10 YEL@17 RED@22 AL2 PT23			23		
G LST@1 MIN@2 GRN@11 YEL@26 RED@31 AL1 PT33				33	
04-NOV-2014 8:51:46 608 IP4.3. ISOL NF					
A <MIN@1 GRN@9 ECG@20 YEL@21 RED@26 AL0 PT27	27				
D MIN@1 GRN@9 YEL@28 RED@33 AL1 PT34		34			
E MIN@1 GRN@10 YEL@12 RED@17 AL1 PT19			19		
G MIN@1 GRN@9 YEL@22 RED@27 AL1 PT29				29	
04-NOV-2014 8:53:33 608 IP4.3. ISOL NF					
A <MIN@1 GRN@9 YEL@37 RED@42 AL1 PT43	43				
D MIN@1 GRN@9 YEL@38 RED@43 AL0 PT43		43			
E MIN@1 GRN@9 ECG@19 YEL@20 RED@25 AL1 PT26			26		
G MIN@1 GRN@10 ECG@31 YEL@33 RED@37 AL1 PT38				38	
04-NOV-2014 8:56:07 608 IP4.3. ISOL NF					
A <MIN@1 GRN@9 YEL@23 RED@28 AL0 PT30	30				
D MIN@1 GRN@8 YEL@27 RED@32 AL1 PT33		33			
E MIN@1 GRN@9 YEL@22 RED@27 AL2 PT28			28		
G LST@1 MIN@2 GRN@10 ECG@20 YEL@21 RED@26 AL1 PT27				27	
04-NOV-2014 8:58:03 608 IP4.3. ISOL NF					
A <LST@1 MIN@2 GRN@10 YEL@27 RED@33 AL1 PT33	33				
D MIN@1 GRN@8 YEL@48 RED@53 AL1 PT34		34			
E LST@1 MIN@2 GRN@10 ECG@19 YEL@21 RED@25 AL1 PT26			26		
G MIN@1 GRN@9 YEL@34 RED@39 AL1 PT41				41	
	895	1185	657	789	
	36	47	26	32	

04-NOV-2014 6:14:43 298 IP1.4. Z+ NF CL126	A	C	D	E	G
A <TG:MIN@1 GRN@9 FG@37 MX@57 P^D:YEL@59 RED@64 MX0 ALO CG47 PT63	63				
C		0			
D MIN@1 GRN@9 YEL@12 RED@17 MX4 AL1 CG62 PT18			18		
E LST@1 MIN@2 GRN@8 YEL@16 RED@21 MX3 AL1 CG80 PT22				22	
G MIN@1 GRN@7 MX@11 P^A:YEL@13 RED@18 MX0 ALO CG95 PT19					19
04-NOV-2014 6:16:49 298 IP1.4. Z+ NF CL124					
A <TG:MIN@1 GRN@9 MX@36 P^C:YEL@38 RED@43 MX0 ALO CG30 PT44	44				
C MIN@1 GRN@7 MX@12 P^D:YEL@14 RED@19 MX0 ALO CG46 PT20		20			
D MIN@1 GRN@9 MX@13 P^E:YEL@17 RED@22 MX0 ALO CG65 PT23			23		
E MIN@1 GRN@7 YEL@17 RED@22 MX2 AL1 CG83 PT23				23	
G MIN@1 GRN@7 MX@11 P^A:YEL@13 RED@18 MX0 ALO CG98 PT19					19
04-NOV-2014 6:18:38 298 IP1.4. Z+ NF CL123					
A <TG:MIN@1 GRN@9 FG@33 MX@53 P^D:YEL@55 RED@60 MX0 ALO CG46 PT61	61				
C		0			
D MIN@1 GRN@9 YEL@11 RED@16 MX6 AL1 CG39 PT17			17		
E MIN@1 GRN@7 YEL@18 RED@24 MX1 ALO CG79 PT25				25	
G MIN@1 GRN@7 MX@11 P^A:YEL@13 RED@18 MX0 ALO CG94 PT19					19
04-NOV-2014 6:21:00 298 IP1.4. Z+ NF CL128					
A <TG:MIN@1 GRN@9 FG@40 MX@45 P^C:YEL@47 RED@52 MX-3 ALO CG32 PT33	33				
C MIN@1 GRN@7 MX@10 P^D:YEL@12 RED@17 MX0 ALO CG43 PT18		18			
D MIN@1 GRN@9 YEL@14 RED@19 MX3 AL1 CG39 PT20			20		
E MIN@1 GRN@7 YEL@14 RED@19 MX8 AL1 CG73 PT20				20	
G MIN@1 GRN@7 MX@13 P^A:YEL@15 RED@20 MX0 ALO CG88 PT21					21
04-NOV-2014 6:23:12 298 IP1.4. Z+ NF CL141					
A <TG:MIN@1 GRN@9 FG@53 MX@77 P^D:YEL@79 RED@84 MX0 ALO CG47 PT83	83				
C		0			
D MIN@1 GRN@9 YEL@12 RED@17 MX8 AL1 CG39 PT18			18		
E MIN@1 GRN@7 YEL@16 RED@21 MX7 AL1 CG74 PT22				22	
G MIN@1 GRN@7 MX@14 P^A:YEL@16 RED@21 MX0 ALO CG89 PT22					22
04-NOV-2014 6:25:39 298 IP1.4. Z+ NF CL147					
A <TG:MIN@1 GRN@9 MX@54 P^C:YEL@56 RED@61 MX0 ALO CG30 PT62	62				
C MIN@1 GRN@7 MX@16 P^D:YEL@18 RED@23 MX0 ALO CG43 PT24		24			
D MIN@1 GRN@9 YEL@11 RED@16 MX10 AL1 CG36 PT17			17		
E MIN@1 GRN@7 YEL@20 RED@25 MX4 AL1 CG73 PT26				26	
G MIN@1 GRN@7 MX@13 P^A:YEL@17 RED@22 MX0 ALO CG88 PT23					23
04-NOV-2014 6:28:11 298 IP1.4. Z+ NF CL154					
A <TG:MIN@1 GRN@9 MX@60 P^C:YEL@62 RED@67 MX0 ALO CG31 PT68	68				
C MIN@1 GRN@7 MX@16 P^D:YEL@18 RED@23 MX0 ALO CG46 PT24		24			
D MIN@1 GRN@9 YEL@12 RED@17 MX9 AL1 CG37 PT18			18		
E MIN@1 GRN@7 YEL@20 RED@25 MX4 AL1 CG73 PT26				26	
G MIN@1 GRN@7 ECG@12 YEL@13 RED@18 MX4 ALO CG85 PT19					19
04-NOV-2014 6:30:46 298 IP1.4. Z+ NF CL161					
A <TG:MIN@1 GRN@9 MX@73 P^C:YEL@75 RED@80 MX0 ALO CG35 PT81	81				
C MIN@1 GRN@7 YEL@13 RED@20 MX3 AL1 CG48 PT21		21			
D LST@1 MIN@2 GRN@10 MX@19 P^E:YEL@21 RED@26 MX0 ALO CG64 PT27			27		
E MIN@1 GRN@7 YEL@19 RED@24 MX3 AL1 CG80 PT25				25	
G MIN@1 GRN@7 YEL@14 RED@19 MX3 AL1 CG92 PT20					20
04-NOV-2014 6:33:40 298 IP1.4. Z+ NF CL163					

A	OTG:MIN@1 RT:1GH2GH3G4G:GRN@9 MX@64 P^C:YEL@66 RED@71 MX0 AL0 CG37 PT72	72			
C	MIN@1 GRN@7 MX@16 YEL@17 RED@22 MX1 AL1 CG51 PT23		23		
D	MIN@1 GRN@9 YEL@19 RED@24 MX2 AL1 CG66 PT25			25	
E	MIN@1 GRN@7 MX@22 P^G:YEL@24 RED@29 MX0 AL0 CG85 PT30				30
G	MIN@1 GRN@7 YEL@10 RED@13 MX7 AL1 CG93 PT16				16
04-NOV-2014 6:36:26 298 IP1.4. Z+ NF CL161					
A	OTG:MIN@1 GRN@9 MX@37 P^C:YEL@39 RED@64 MX0 AL0 CG37 PT65	65			
C	MIN@1 GRN@7 MX@16 P^D:YEL@18 RED@23 MX0 AL0 CG52 PT24		24		
D	MIN@1 GRN@9 YEL@19 RED@24 MX2 AL1 CG68 PT25			25	
E	MIN@1 W2GRN@7 MX@22 P^G:YEL@27 RED@32 MX-3 AL-2 CG89 PT38				33
G	MIN@1 GRN@7 MX@14 P^A:YEL@16 RED@21 MX0 AL0 CG4 PT22				22
04-NOV-2014 6:39:13 298 IP1.4. Z+ NF CL149					
A	OTG:MIN@1 GRN@9 FG@32 MX@43 P^C:YEL@45 RED@50 MX-11 AL0 CG38 PT51	51			
C	MIN@1 MX@3 P^D:GRN@7 YEL@8 RED@13 MX-1 AL0 CG47 PT14		14		
D	MIN@1 GRN@9 MX@18 ECG@19 YEL@20 RED@25 MX0 AL0 CG65 PT26			26	
E	MIN@1 GRN@7 YEL@18 RED@23 MX6 AL1 CG81 PT24				24
G	LST@1 MIN@2 GRN@8 YEL@13 RED@18 MX3 AL1 CG94 PT19				19
04-NOV-2014 6:41:29 298 IP1.4. Z+ NF CL149					
A	OTG:MIN@1 GRN@9 MX@47 P^C:YEL@49 RED@54 MX0 AL0 CG30 PT55	55			
C	MIN@1 GRN@7 MX@16 P^D:YEL@18 RED@23 MX0 AL0 CG46 PT24		24		
D	MIN@1 GRN@9 YEL@10 RED@13 MX11 AL1 CG57 PT16			16	
E	MIN@1 GRN@7 MX@22 YEL@23 RED@28 MX1 AL1 CG76 PT29				29
G	MIN@1 GRN@7 MX@13 P^A:YEL@17 RED@22 MX0 AL0 CG91 PT23				23
04-NOV-2014 6:43:56 298 IP1.4. Z+ NF CL151					
A	OTG:MIN@1 GRN@9 MX@33 P^C:YEL@35 RED@60 MX0 AL0 CG31 PT61	61			
C	MIN@1 GRN@7 MX@16 P^D:YEL@18 RED@23 MX0 AL0 CG47 PT24		24		
D	MIN@1 GRN@9 YEL@13 RED@20 MX6 AL1 CG61 PT21			21	
E	MIN@1 GRN@7 MX@22 P^G:YEL@24 RED@29 MX0 AL0 CG80 PT30				30
G	MIN@1 GRN@7 MX@13 P^A:YEL@17 RED@22 MX0 AL0 CG95 PT23				23
04-NOV-2014 6:46:33 298 IP1.4. Z+ NF CL153					
A	OTG:MIN@1 GRN@9 MX@49 P^C:YEL@51 RED@56 MX0 AL0 CG31 PT57	57			
C	MIN@1 GRN@7 MX@16 P^D:YEL@18 RED@23 MX0 AL0 CG45 PT24		24		
D	MIN@1 GRN@9 MX@19 P^E:YEL@21 RED@26 MX0 AL0 CG62 PT27			27	
E	MIN@1 GRN@7 MX@22 P^G:YEL@24 RED@28 MX1 AL1 CG80 PT29				29
G	LST@1 MIN@2 GRN@8 MX@13 P^A:YEL@17 RED@22 MX0 AL0 CG94 PT23				23
04-NOV-2014 6:49:13 298 IP1.4. Z+ NF CL163					
A	OTG:MIN@1 GRN@9 MX@61 P^C:YEL@63 RED@68 MX0 AL0 CG36 PT69	69			
C	MIN@1 GRN@7 MX@16 P^D:YEL@18 RED@23 MX0 AL0 CG51 PT24		24		
D	MIN@1 GRN@9 MX@19 P^E:YEL@21 RED@26 MX0 AL0 CG67 PT27			27	
E	MIN@1 GRN@7 MX@22 P^G:YEL@24 RED@29 MX0 AL0 CG86 PT30				30
G	MIN@1 GRN@7 MX@13 P^A:YEL@17 RED@22 MX0 AL0 CG0 PT23				23
04-NOV-2014 6:52:08 298 IP1.4. Z+ NF CL163					
A	OTG:MIN@1 GRN@9 MX@51 P^C:YEL@53 RED@58 MX0 AL0 CG36 PT59	59			
C	MIN@1 GRN@7 MX@16 P^D:YEL@18 RED@23 MX0 AL0 CG50 PT24		24		
D	MIN@1 GRN@9 YEL@11 RED@16 MX10 AL1 CG60 PT17			17	
E	MIN@1 GRN@7 MX@22 P^G:YEL@24 RED@29 MX0 AL0 CG78 PT30				30
G	MIN@1 GRN@7 YEL@12 RED@17 MX3 AL1 CG89 PT18				18
04-NOV-2014 6:54:36 298 IP1.4. Z+ NF CL166					
A	OTG:MIN@1 GRN@9 FG@72 MX@96 P^D:YEL@98 RED@103 MX0 AL0 CG52 PT104	104			

C		0			
D MIN@1 GRN@9 ECG@18 YEL@19 RED@24 MX2 ALO CG68 PT25			25		
E MIN@1 GRN@7 MX@22 P@G:YEL@24 RED@29 MX0 ALO CG86 PT30				30	
G MIN@1 GRN@7 YEL@14 RED@19 MX3 AL1 CG98 PT20					20
04-NOV-2014 6:57:35 298 IP1.4. Z+ NFCL164					
A @TG:MIN@1 GRN@9 MX@33 P@C:YEL@37 RED@62 MX0 ALO CG38 PT63	63				
C MIN@1 GRN@7 MX@16 P@D:YEL@18 RED@23 MX0 ALO CG33 PT24		24			
D MIN@1 GRN@9 MX@19 P@E:YEL@21 RED@26 MX0 ALO CG70 PT27			27		
E MIN@1 GRN@7 MX@22 P@G:YEL@24 RED@29 MX0 ALO CG89 PT30				30	
G MIN@1 GRN@7 MX@15 P@A:YEL@17 RED@22 MX0 ALO CG4 PT23					23
04-NOV-2014 7:00:22 298 IP1.4. Z+ NFCL152					
A @MIN@1 GRN@9 FG@34 MX@38 P@D:YEL@60 RED@65 MX0 ALO CG47 PT66	66				
C		0			
D MIN@1 GRN@9 YEL@16 RED@21 MX3 AL1 CG62 PT22			22		
E MIN@1 GRN@7 MX@22 P@G:YEL@24 RED@29 MX0 ALO CG81 PT30				30	
G MIN@1 GRN@7 YEL@11 RED@16 MX6 AL1 CG92 PT17					17
04-NOV-2014 7:02:37 298 IP1.4. Z+ NFCL152					
A @TG:MIN@1 GRN@9 FG@52 MX@76 P@D:YEL@78 RED@83 MX0 ALO CG47 PT84	84				
C		0			
D MIN@1 GRN@9 YEL@16 RED@21 MX3 AL1 CG62 PT22			22		
E MIN@1 GRN@7 MX@22 P@G:YEL@24 RED@29 MX0 ALO CG81 PT30				30	
G MIN@1 GRN@7 MX@15 YEL@16 RED@21 MX1 AL1 CG96 PT22					22
04-NOV-2014 7:05:15 298 IP1.4. Z+ NFCL153					
A @TG:MIN@1 GRN@9 MX@47 P@C:YEL@49 RED@54 MX0 ALO CG31 PT35	35				
C MIN@1 GRN@7 MX@16 P@D:YEL@18 RED@23 MX0 ALO CG47 PT24		24			
D MIN@1 GRN@9 MX@19 P@E:YEL@21 RED@26 MX0 ALO CG64 PT27			27		
E MIN@1 GRN@7 MX@22 P@G:YEL@24 RED@29 MX0 ALO CG84 PT30				30	
G MIN@1 GRN@7 MX@15 YEL@16 RED@21 MX1 AL1 CG98 PT22					22
04-NOV-2014 7:07:53 298 IP1.4. Z+ NFCL155					
A @TG:MIN@1 GRN@9 MX@46 P@C:YEL@48 RED@53 MX0 ALO CG31 PT34	34				
C MIN@1 GRN@7 MX@16 P@D:YEL@18 RED@23 MX0 ALO CG46 PT24		24			
D MIN@1 GRN@9 YEL@13 RED@18 MX8 AL1 CG57 PT19			19		
E MIN@1 GRN@7 MX@22 P@G:YEL@24 RED@29 MX0 ALO CG76 PT30				30	
G MIN@1 GRN@7 MX@15 P@A:YEL@17 RED@22 MX0 ALO CG90 PT23					23
04-NOV-2014 7:10:23 298 IP1.4. Z+ NFCL164					
A @TG:MIN@1 GRN@9 FG@68 MX@69 P@C:YEL@71 RED@76 MX-1 ALO CG37 PT77	77				
C MIN@1 GRN@7 YEL@15 RED@20 MX2 AL1 CG50 PT21		21			
D MIN@1 GRN@9 MX@19 P@E:YEL@21 RED@26 MX0 ALO CG67 PT27			27		
E MIN@1 GRN@7 MX@22 P@G:YEL@24 RED@29 MX0 ALO CG85 PT30				30	
G MIN@1 GRN@7 YEL@14 RED@19 MX3 AL1 CG97 PT20					20
04-NOV-2014 7:13:18 298 IP1.4. Z+ NFCL162					
A @TG:MIN@1 GRN@9 FG@55 MX@66 P@C:YEL@68 RED@73 MX-11 ALO CG44 PT74	74				
C MIN@1 MX@5 P@D:GRN@7 YEL@8 RED@13 MX-1 ALO CG52 PT14		14			
D MIN@1 GRN@9 YEL@15 RED@20 MX8 AL1 CG65 PT21			21		
E MIN@1 GRN@7 MX@25 P@G:YEL@27 RED@32 MX0 ALO CG86 PT33				33	
G MIN@1 GRN@7 MX@15 P@A:YEL@17 RED@22 MX0 ALO CG0 PT23					23
	1585	395	532	667	499
	66	16	22	28	21

04-NOV-2014 8:01:32	298 IP1.4.	Z+ NF CL167				
A	MIN@1 GRN@9 MX@62 P^C:YEL@64 RED@69 MX0 AL0 CG37 PT70	70				
C	MIN@1 GRN@7 MX@16 P^D:YEL@18 RED@23 MX0 AL0 CG32 PT24		24			
D	MIN@1 GRN@9 YEL@18 RED@23 MX3 AL1 CG66 PT24			24		
E	MIN@1 GRN@7 MX@22 P^G:YEL@24 RED@29 MX0 AL0 CG84 PT30				30	
G	MIN@1 GRN@7 MX@15 P^A:YEL@17 RED@22 MX0 AL0 CG98 PT23					23
04-NOV-2014 8:04:43	298 IP1.4.	Z+ NF CL168				
A	MIN@1 GRN@9 MX@39 P^C:YEL@61 RED@66 MX0 AL0 CG38 PT67	67				
C	MIN@1 GRN@7 MX@16 P^D:YEL@18 RED@23 MX0 AL0 CG32 PT24		24			
D	MIN@1 GRN@9 MX@19 P^E:YEL@21 RED@26 MX0 AL0 CG69 PT27			27		
E	MIN@1 GRN@7 MX@22 P^G:YEL@24 RED@29 MX0 AL0 CG87 PT30				30	
G	MIN@1 GRN@7 MX@15 P^A:YEL@17 RED@22 MX0 AL0 CG1 PT23					23
04-NOV-2014 8:07:34	298 IP1.4.	Z+ NF CL166				
A	MIN@1 GRN@9 MX@32 P^C:YEL@34 RED@39 MX0 AL0 CG37 PT60	60				
C	MIN@1 GRN@7 MX@16 P^D:YEL@18 RED@23 MX0 AL0 CG32 PT24		24			
D	MIN@1 GRN@9 MX@22 YEL@23 RED@28 MX1 AL1 CG69 PT29			29		
E	MIN@1 GRN@7 MX@25 P^G:YEL@27 RED@32 MX0 AL0 CG90 PT33				33	
G	MIN@1 GRN@7 MX@15 P^A:YEL@17 RED@22 MX0 AL0 CG4 PT23					23
04-NOV-2014 8:10:23	298 IP2.4.	Z+ NF CL158				
A	MIN@1 GRN@9 MX@34 P^C:YEL@36 RED@41 MX0 AL0 CG30 PT42	42				
C	MIN@1 GRN@7 MX@16 P^D:YEL@18 RED@23 MX0 AL0 CG43 PT24		24			
D	MIN@1 GRN@9 YEL@18 RED@23 MX6 AL1 CG61 PT24			24		
E	MIN@1 W2GRN@7 MX@25 P^G:YEL@27 RED@33 MX-1 AL-1 CG82 PT34				34	
G	MIN@1 GRN@7 MX@15 P^A:YEL@17 RED@22 MX0 AL0 CG97 PT23					23
04-NOV-2014 8:12:50	298 IP2.4.	Z+ NF CL158				
A	MIN@1 GRN@9 MX@45 P^C:YEL@47 RED@52 MX0 AL0 CG30 PT33	33				
C	MIN@1 GRN@7 MX@16 P^D:YEL@18 RED@23 MX0 AL0 CG43 PT24		24			
D	MIN@1 GRN@9 YEL@20 RED@25 MX7 AL1 CG61 PT26			26		
E	MIN@1 GRN@7 MX@28 P^G:YEL@30 RED@35 MX0 AL0 CG84 PT36				36	
G	MIN@1 GRN@7 MX@15 P^A:YEL@17 RED@22 MX0 AL0 CG98 PT23					23
04-NOV-2014 8:15:32	298 IP3.4.	Z+ NF CL160				
A	MIN@1 GRN@9 MX@39 P^C:YEL@41 RED@46 MX0 AL0 CG27 PT47	47				
C	MIN@1 GRN@7 MX@16 P^D:YEL@18 RED@23 MX0 AL0 CG42 PT24		24			
D	MIN@1 GRN@9 YEL@18 RED@23 MX9 AL1 CG37 PT24			24		
E	MIN@1 GRN@7 MX@28 P^G:YEL@30 RED@35 MX0 AL0 CG79 PT36				36	
G	MIN@1 GRN@7 MX@15 P^A:YEL@17 RED@22 MX0 AL0 CG93 PT23					23
04-NOV-2014 8:18:06	298 IP3.4.	Z+ NF CL162				
A	MIN@1 GRN@9 MX@49 P^C:YEL@51 RED@56 MX0 AL0 CG28 PT37	37				
C	MIN@1 GRN@7 MX@16 P^D:YEL@18 RED@23 MX0 AL0 CG43 PT24		24			
D	MIN@1 GRN@9 YEL@20 RED@25 MX7 AL1 CG39 PT26			26		
E	MIN@1 GRN@7 MX@28 P^G:YEL@30 RED@35 MX0 AL0 CG81 PT36				36	
G	MIN@1 GRN@7 MX@15 P^A:YEL@17 RED@22 MX0 AL0 CG96 PT23					23
04-NOV-2014 8:20:52	298 IP3.4.	Z+ NF CL162				
A	MIN@1 GRN@9 MX@44 P^C:YEL@46 RED@51 MX0 AL0 CG27 PT32	32				
C	MIN@1 GRN@7 MX@16 P^D:YEL@18 RED@23 MX0 AL0 CG42 PT24		24			
D	MIN@1 GRN@9 YEL@17 RED@22 MX10 AL1 CG36 PT23			23		
E	MIN@1 W2GRN@7 MX@28 P^G:YEL@30 RED@35 MX0 AL0 CG78 PT36				36	
G	MIN@1 GRN@7 MX@15 P^A:YEL@17 RED@22 MX0 AL0 CG92 PT23					23

A	◀TG:MIN01 GRN09 MX063 P^C:YEL067 RED072 MX0 ALO CG31 PT73	73				
C	MIN01 GRN07 MX016 P^D:YEL018 RED023 MX0 ALO CG46 PT24		24			
D	MIN01 GRN09 YEL022 RED027 MX2 AL1 CG63 PT28			28		
E	MIN01 GRN07 MX025 P^G:YEL027 RED032 MX0 ALO CG84 PT33				33	
G	MIN01 GRN07 MX015 P^A:YEL017 RED022 MX0 ALO CG98 PT23					23
04-NOV-2014 8:47:25 298 IP2.4. Z+ NFCL161						
A	◀TG:MIN01 GRN09 MX046 P^C:YEL048 RED053 MX0 ALO CG32 PT34	34				
C	MIN01 GRN07 MX016 P^D:YEL018 RED023 MX0 ALO CG47 PT24		24			
D	MIN01 GRN09 YEL013 RED018 MX14 AL1 CG59 PT19			19		
E	MIN01 GRN07 MX028 P^G:YEL030 RED035 MX0 ALO CG82 PT36				36	
G	MIN01 GRN07 MX015 P^A:YEL017 RED022 MX0 ALO CG96 PT23					23
04-NOV-2014 8:50:01 298 IP3.4. Z+ NFCL159						
A	◀TG:MIN01 GRN09 MX041 P^C:YEL043 RED048 MX0 ALO CG28 PT49	49				
C	MIN01 GRN07 MX016 P^D:YEL018 RED023 MX0 ALO CG43 PT24		24			
D	MIN01 GRN09 MX025 P^E:YEL027 RED032 MX0 ALO CG64 PT33			33		
E	MIN01 GRN07 MX028 P^G:YEL030 RED035 MX0 ALO CG88 PT36				36	
G	MIN01 GRN07 MX015 P^A:YEL017 RED022 MX0 ALO CG2 PT23					23
04-NOV-2014 8:52:46 298 IP3.4. Z+ NFCL155						
A	◀MIN01 GRN09 MX028 P^C:YEL030 RED035 MX0 ALO CG26 PT36	36				
C	MIN01 GRN07 MX016 P^D:YEL018 RED023 MX0 ALO CG41 PT24		24			
D	MIN01 GRN09 MX022 YEL023 RED028 MX1 AL1 CG60 PT29			29		
E	MIN01 GRN07 MX025 P^G:YEL027 RED032 MX0 ALO CG82 PT33				33	
G	MIN01 GRN07 MX015 P^A:YEL017 RED022 MX0 ALO CG97 PT23					23
04-NOV-2014 8:55:11 298 IP2.4. Z+ NFCL154						
A	◀TG:MIN01 GRN09 MX041 P^C:YEL043 RED048 MX0 ALO CG28 PT49	49				
C	MIN01 GRN07 MX016 P^D:YEL018 RED023 MX0 ALO CG43 PT24		24			
D	MIN01 GRN09 MX022 P^E:YEL024 RED029 MX0 ALO CG63 PT30			30		
E	MIN01 GRN07 MX025 P^G:YEL027 RED032 MX0 ALO CG84 PT33				33	
G	MIN01 GRN07 MX015 P^A:YEL017 RED022 MX0 ALO CG99 PT23					23
04-NOV-2014 8:57:30 298 IP2.4. Z+ NFCL156						
A	◀MIN01 GRN09 MX040 P^C:YEL042 RED047 MX0 ALO CG29 PT48	48				
C	MIN01 GRN07 MX016 P^D:YEL018 RED023 MX0 ALO CG44 PT24		24			
D	MIN01 GRN09 MX019 P^E:YEL021 RED026 MX0 ALO CG61 PT27			27		
E	MIN01 GRN07 MX022 P^G:YEL024 RED029 MX0 ALO CG80 PT30				30	
G	MIN01 GRN07 MX015 P^A:YEL017 RED022 MX0 ALO CG94 PT23					23
		1164	525	570	745	506
		53	24	26	34	23

APPENDIX D

Record Sheet

Date:

THL/RTL

Intersection Name and Bound:

- Detector #

Cycle number	THL queue at end of THL red	No of cars turning right at the beginning of Thr. L green	RTL queue at end of red arrow	Blockage Y/N	Overflow Y/N	Comments

APPENDIX E

SAMPLE OF SCATS REPORTS

SCATS Traffic Reporter

On Monday 21 July 2014 14:57 Page: 2 of 3

Site: 441 On Wednesday 16-July-2014

Traffic Flow filename:KIN_20140716.vs

AM Total: 520 AM peak 109 09:15 - 10:15

	12:	13:	14:	15:	16:	17:	18:	19:	20:	21:	22:	23:
:15	15	16	23	42	35	44	39	20	10	4	7	1
:30	26	26	24	33	40	40	30	11	6	11	7	2
:45	23	23	19	44	51	44	28	15	17	13	4	0
:60	18	24	27	41	31	31	23	21	5	9	3	6
Hourly												
Total	82	89	93	160	157	159	120	67	38	37	21	9

Peak-hour

PM Total: 1032 PM peak 160 15:45 - 16:45

Daily Total 1552

Approach 5, Detectors: 8-9

	00:	01:	02:	03:	04:	05:	06:	07:	08:	09:	10:	11:
:15	4	1	1	0	4	4	9	32	55	67	87	103
:30	5	1	0	1	2	9	10	33	37	62	103	104
:45	3	1	1	1	0	12	29	35	57	65	72	84
:60	1	0	1	2	2	15	36	54	77	99	95	127
Hourly												
Total	13	3	3	4	8	40	84	154	226	293	357	418

Peak-hour
volume

AM Total: 1603 AM peak 418 11:00 - 12:00

	12:	13:	14:	15:	16:	17:	18:	19:	20:	21:	22:	23:
:15	115	84	99	72	97	114	102	74	45	30	23	19
:30	93	89	70	78	119	140	98	75	34	28	31	11
:45	94	86	90	77	119	131	127	65	31	27	20	16
:60	78	64	72	97	112	122	102	87	35	27	16	14
Hourly												
Total	380	323	331	324	447	507	429	261	145	112	90	60

PM Total: 3409 PM peak 507 17:00 - 18:00

Daily Total 5012

Approach 6, Detector: 10

	00:	01:	02:	03:	04:	05:	06:	07:	08:	09:	10:	11:
:15	4	4	2	1	1	5	2	13	24	38	36	57
:30	7	0	4	2	2	2	12	15	30	45	54	48
:45	4	1	3	0	1	5	14	21	42	46	55	50
:60	3	2	3	4	3	7	18	28	64	60	50	47
Hourly												
Total	18	7	12	7	7	19	46	77	160	189	195	202

AM Total: 939 AM peak 216 10:15 - 11:15